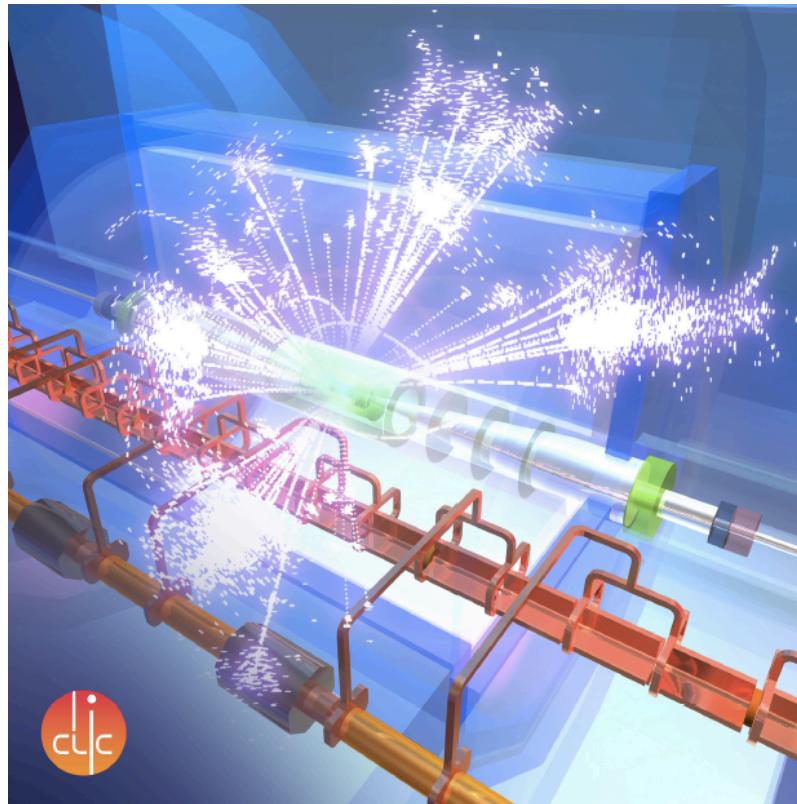


Potential for New Physics searches in e^+e^- collisions at CLIC



Lucie Linssen, CERN
on behalf of the CLIC detector and physics study

Outline, references

Outline

- CLIC machine, physics, energy staging
- Top
- SM Higgs, Higgs multiplet, Higgs compositeness
- SUSY
- Z' , contact interactions and other physics reach
- Summary and outlook

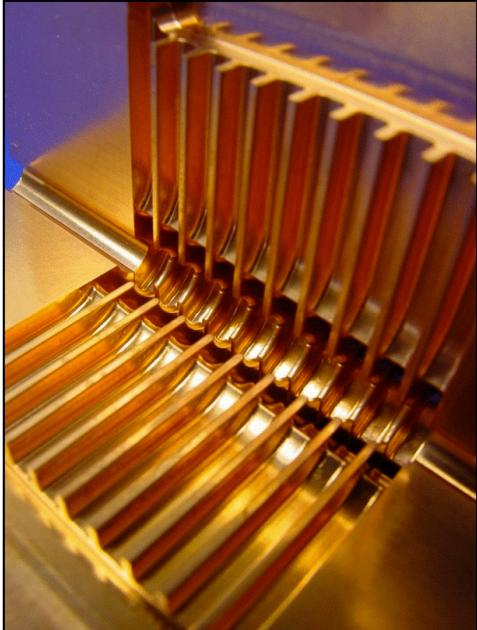
References

- CLIC CDR (#1), A Multi-TeV Linear Collider based on CLIC Technology, <https://edms.cern.ch/document/1234244/>
- CLIC CDR (#2), Physics and Detectors at CLIC, arXiv:1202.5904
- CLIC CDR (#3), The CLIC Programme: towards a staged e^+e^- Linear Collider exploring the Terascale, arXiv:1209.2543
- Brau et al., the physics case for an e^+e^- linear collider, arXiv:1210.0202
- D. Dannheim et al., CLIC e^+e^- linear collider studies, Input to the Snowmass process 2013 (submitted to the accelerator WG for Snowmass)

CLIC in just a few words



CLIC is the most mature option for a multi-TeV scale future e^+e^- collider



- 2-beam acceleration scheme at room temperature
- Gradient 100 MV/m => \sqrt{s} up to 3 TeV
- Staging scenario ~350 GeV to 3 TeV
- High luminosity (a few $10^{34} \text{ cm}^{-2}\text{s}^{-1}$)

focus is on energy frontier reach !

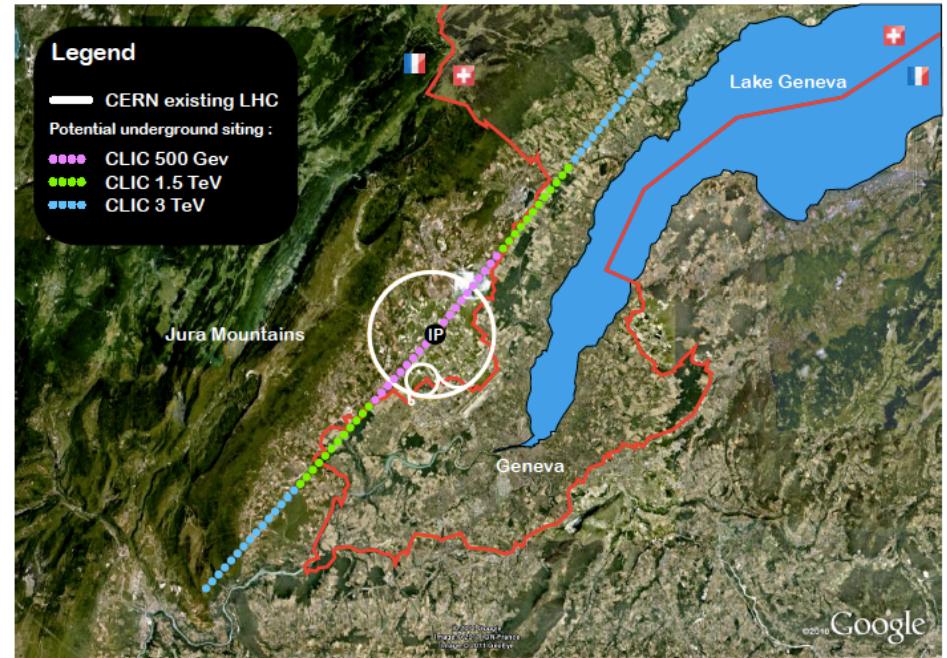
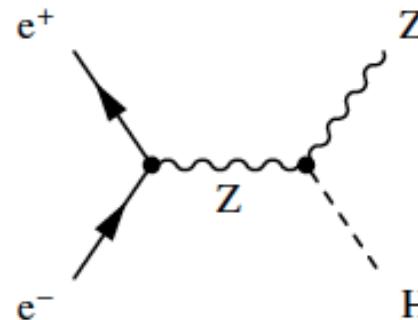
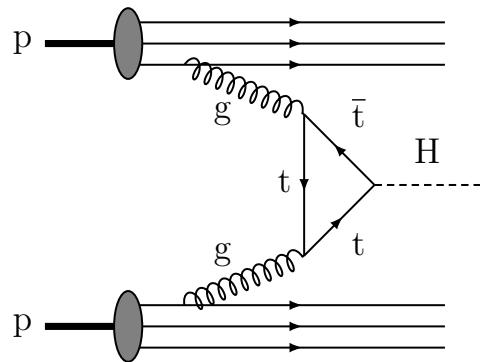


Fig. 7.2: CLIC footprints near CERN, showing various implementation stages [5].
Lucie Linssen, BSM, BNL-Snowmass, 5 April 2013

hadron vs. lepton colliders



p-p collisions	e^+e^- collisions
Proton is compound object \rightarrow Initial state not known event-by-event \rightarrow Limits achievable precision	e^+/e^- are point-like \rightarrow Initial state well defined (\sqrt{s} / polarization) \rightarrow High-precision measurements
Circular colliders feasible	Linear Colliders (avoid synchrotron rad.)
High rates of QCD backgrounds \rightarrow Complex triggering schemes \rightarrow High levels of radiation	Cleaner experimental environment \rightarrow trigger-less readout \rightarrow Low radiation levels
\sqrt{s} constrained by design	\sqrt{s} can be tuned \rightarrow Threshold scans
High cross-sections for colored-states	Superior sensitivity for electro-weak states

Physics potential of LHC/HL-LHC and high-energy e^+e^- collider are complementary !

CLIC physics potential

In particular, e^+e^- collisions at CLIC bring:

- Precision Higgs physics (SM and BSM), precision top physics
- Other precision measurements, like WW scattering, single W production
- Direct searches to weakly coupled BSM states, e.g. sleptons, gauginos
-

Physics highlights include

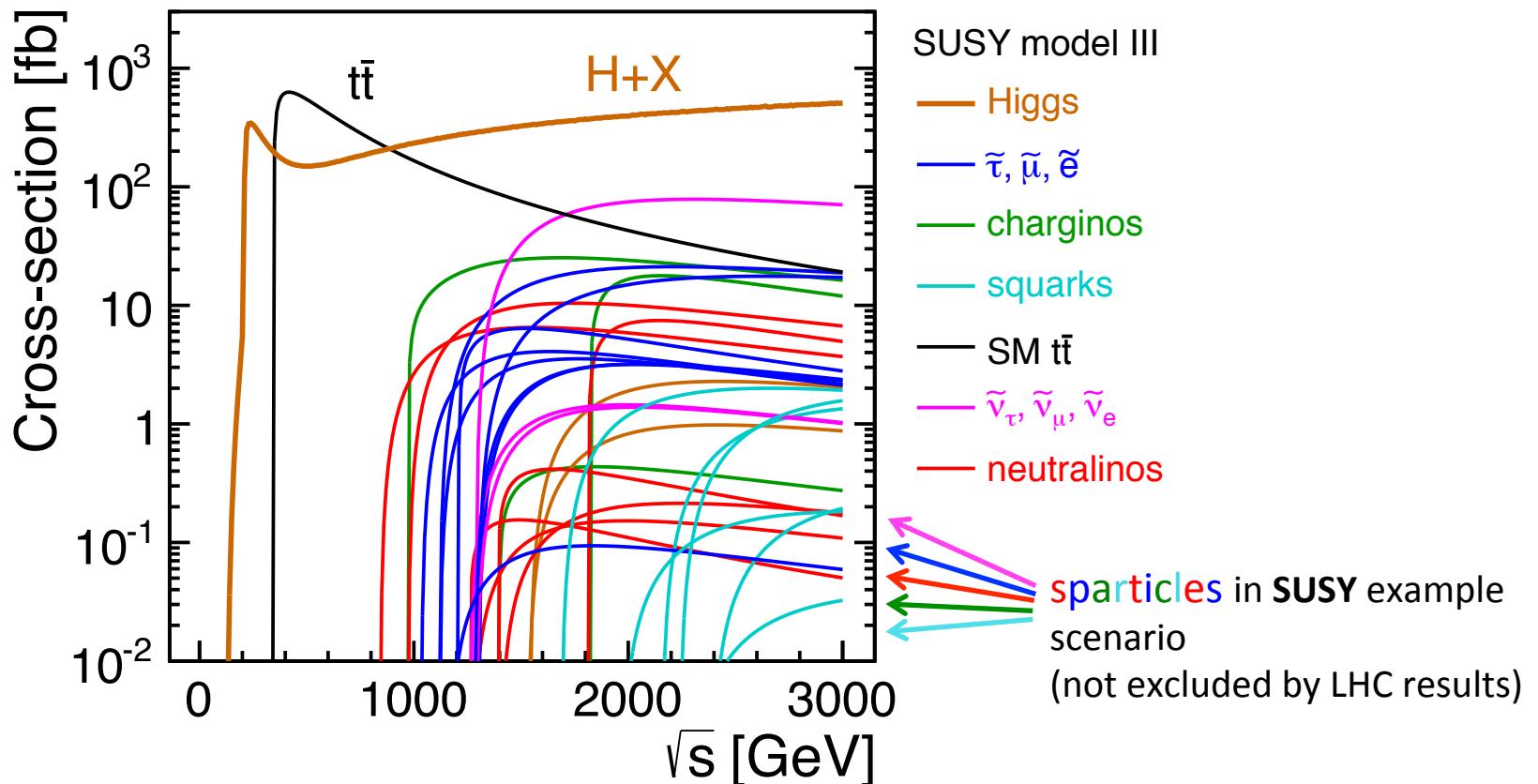
- Higgs
- Top
- SUSY
- Z'
- Contact interactions
- Extra dimensions
-

Experimental sensitivities are now well understood, most studies based on

- Full GEANT4 simulation/reconstruction
- Including pile-up of background

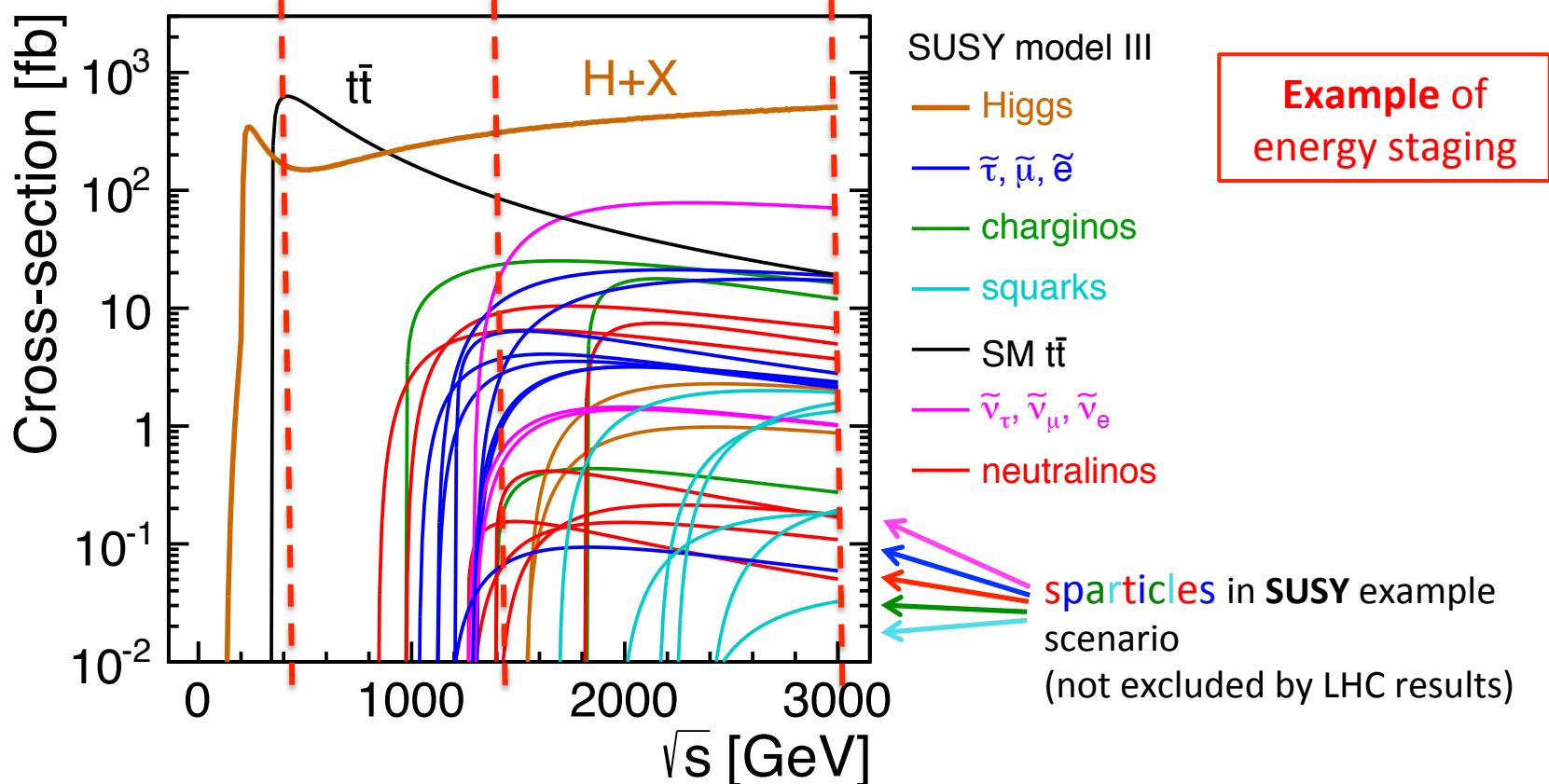
physics at CLIC

- Precision SM measurements: Higgs, top $\rightarrow \sqrt{s} \lesssim 350$ GeV, and up to 3 TeV
- Discovery of new physics at TeV scale,
unique sensitivity to particles with electroweak charge
- New Physics model discrimination, e.g. SUSY \rightarrow up to $\sqrt{s} \sim 3$ TeV



physics at CLIC

- Precision SM measurements: Higgs, top $\rightarrow \sqrt{s} \lesssim 350$ GeV, and up to 3 TeV
- Discovery of new physics at TeV scale,
unique sensitivity to particles with electroweak charge
- New Physics model discrimination, e.g. SUSY \rightarrow up to $\sqrt{s} \sim 3$ TeV



integrated luminosity

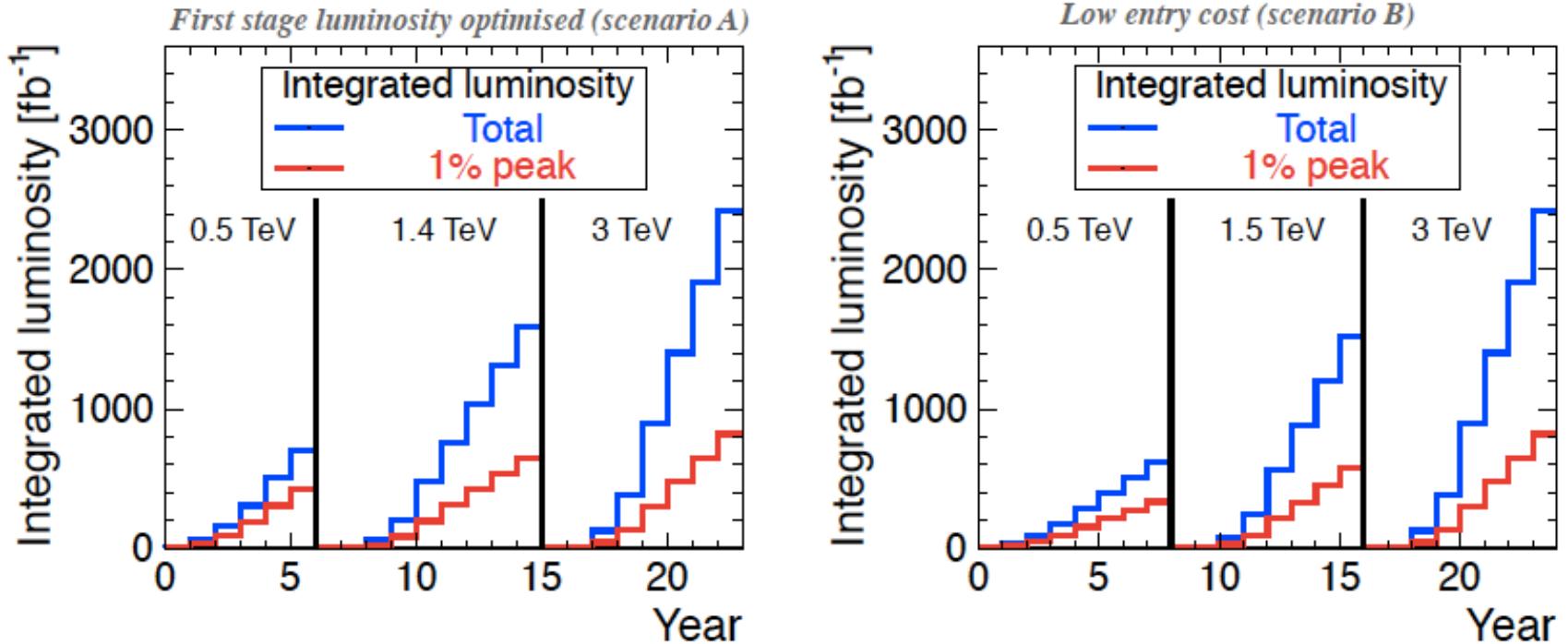


Fig. 5.2: Integrated luminosity in the scenarios optimised for luminosity in the first energy stage (left) and optimised for entry costs (right). Years are counted from the start of beam commissioning. These figures include luminosity ramp-up of four years (5%, 25%, 50%, 75%) in the first stage and two years (25%, 50%) in subsequent stages.

Based on 200 days/year at 50% efficiency (accelerator + data taking combined)

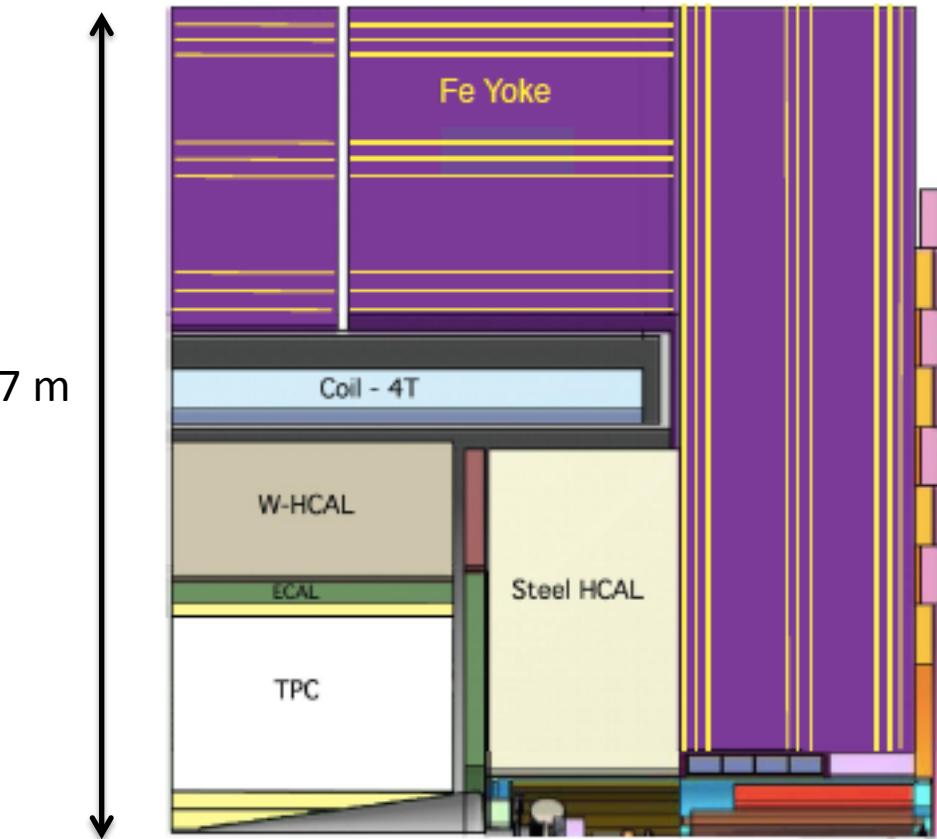
CLIC_ILD and CLIC_SiD



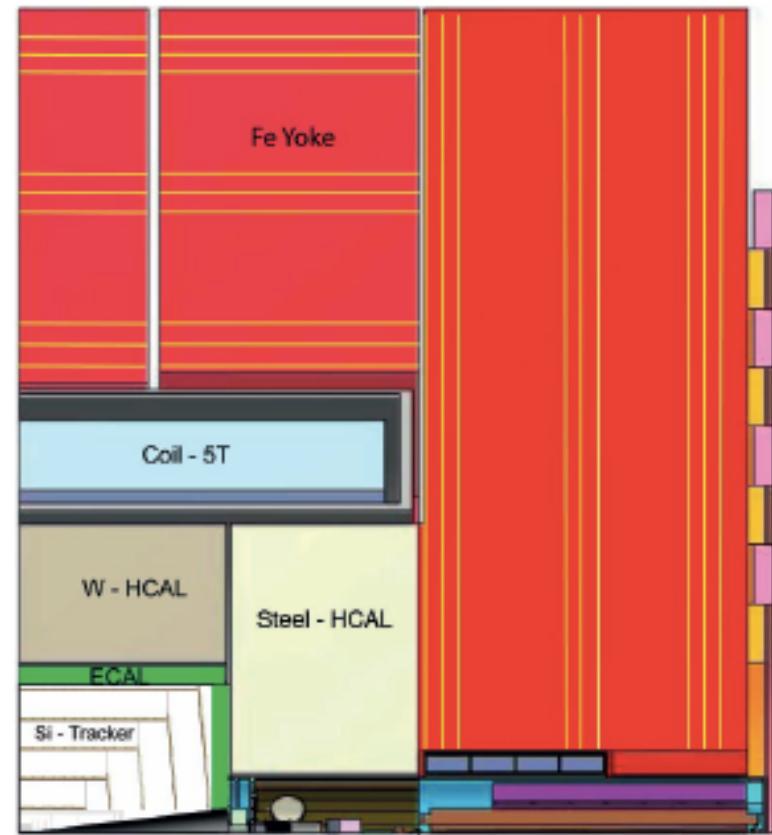
Two general-purpose CLIC detector concepts

Based on initial ILC concepts (ILD and SiD), adapted to CLIC conditions

CLIC_ILD



CLIC_SiD



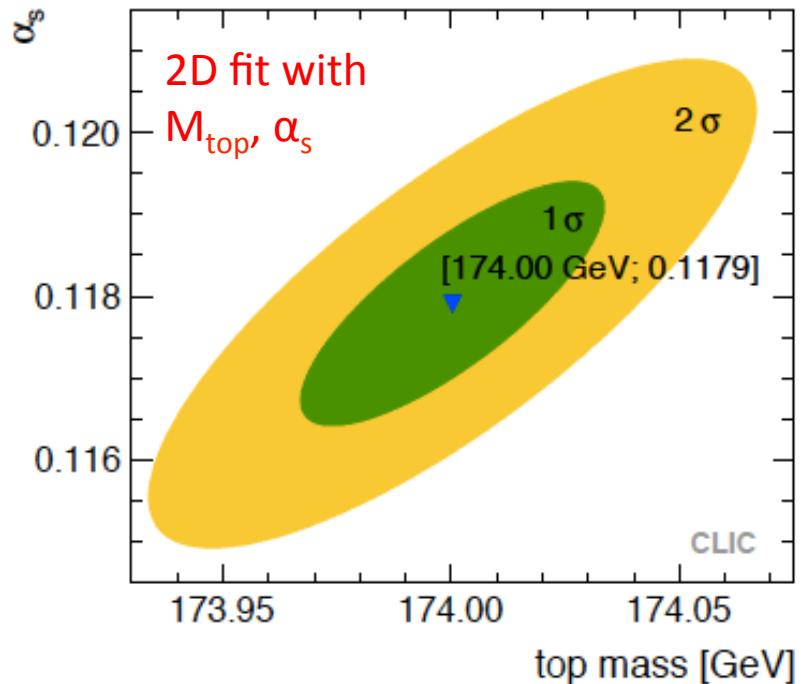
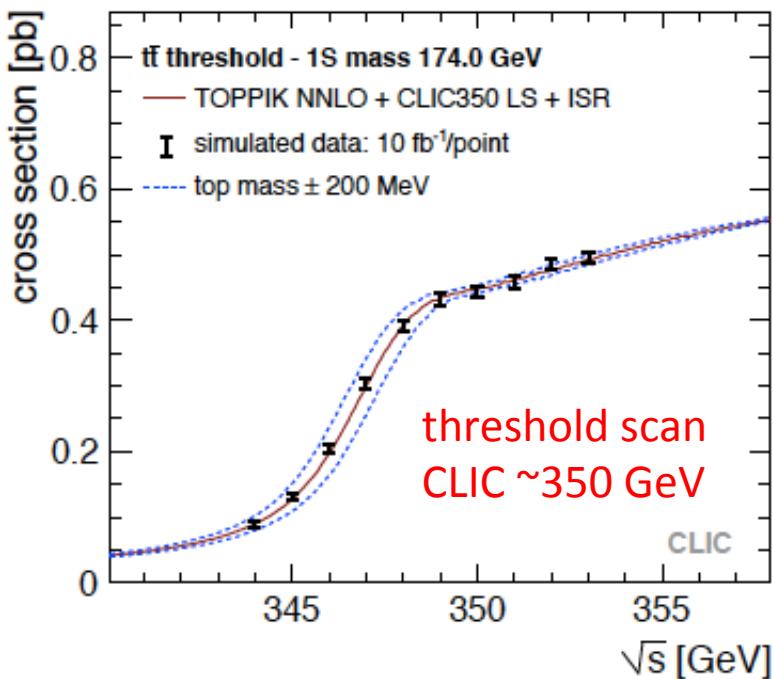
Most physics studies in this talk => full detector simulation + background overlays

Precision top physics 350, 500 GeV



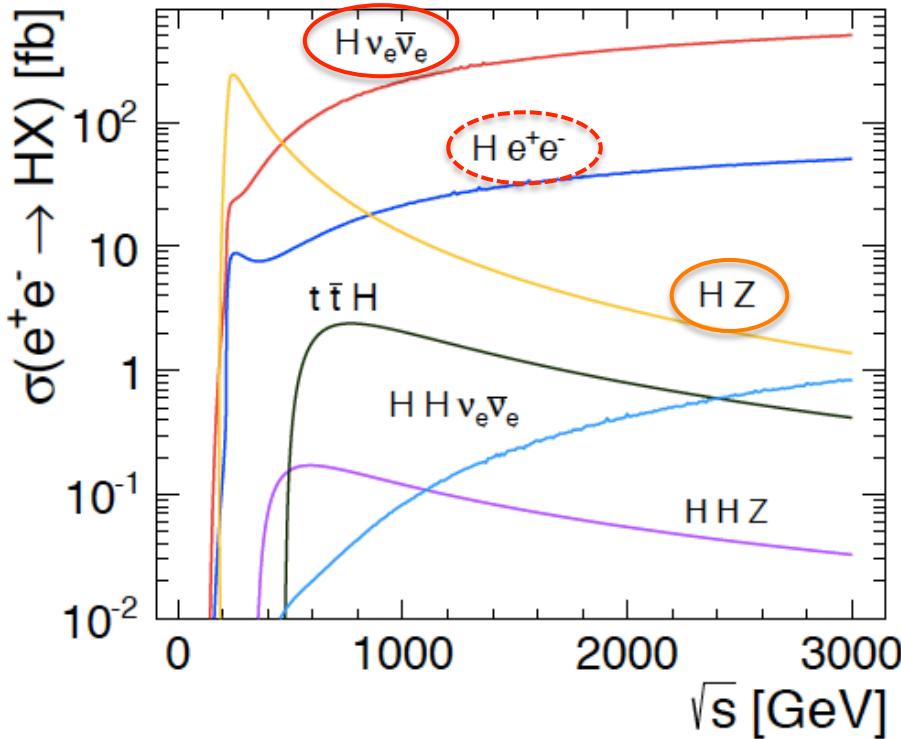
- e+e- collisions at and above the ttbar threshold provide two complementary ways of measuring the top quark mass:
 - Direct reconstruction (<= studied for CLIC at 500 GeV)
 - Threshold scan (<= studied for CLIC around 350 GeV)
- For both, total uncertainties on the level of 100 MeV are within reach with 100 fb^{-1} , highest precision (theoretically clean) with threshold scan

See: arXiv:1303.3758

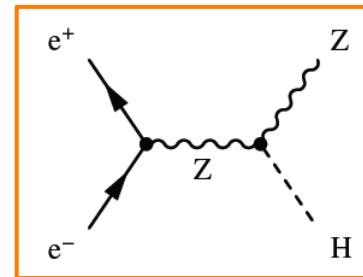


Other options for top physics at CLIC include: top couplings, LR asymmetries, boosted tops...

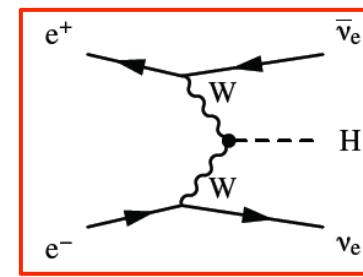
Higgs physics at CLIC (1)



Dominant processes:



Higgsstrahlung
decreases with \sqrt{s}



$W(Z)$ - fusion
increases with \sqrt{s}

Available luminosity increases with \sqrt{s} !

$M_h = 125$ GeV	350 GeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \rightarrow ZH)$	129 fb	6 fb	1 fb
$\sigma(e^+e^- \rightarrow H\nu\nu)$	30 fb	309 fb	484 fb
Int \mathcal{L} (4-5 yrs)	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	65000	7500	2000
# $H\nu\nu$ events	15000	460000	970000

Higgs physics at CLIC (2)

Benchmarking results obtained so far:

	Observable	stat. uncertainty
HZ	σ	4%
HZ	mass	120 MeV
$H \rightarrow \pi\pi$	$\sigma \times BR$	6.2%
HZ / Hvv	σ/σ	5%
HZ, $H \rightarrow bb$	mass	100 MeV
$H \rightarrow \pi\pi$	$\sigma \times BR$	3.7%
HHvv	self-coupling λ	30%
ttH	σ	8%
$H \rightarrow bb$	$\sigma \times BR$	0.2%
$H \rightarrow cc$	$\sigma \times BR$	3.2%
$H \rightarrow \mu\mu$	$\sigma \times BR$	15%
HHvv	self-coupling λ	16%

350 GeV

500 GeV

1.4 TeV

<= estimate based on 1 TeV ILC result

3 TeV

All based on full detector simulation with beam-induced background and physics backgrounds
 No polarisation assumed (80% electron polarisation will enhance Hvv/HHvv signals by 80%)

Complete set of Higgs will be ready for Minneapolis meeting
 (Incl. couplings to Z, bb, cc, gg, W^*W , $\gamma\gamma$, γZ , $\pi\pi$, $\mu\mu$ and ttH and self-coupling)

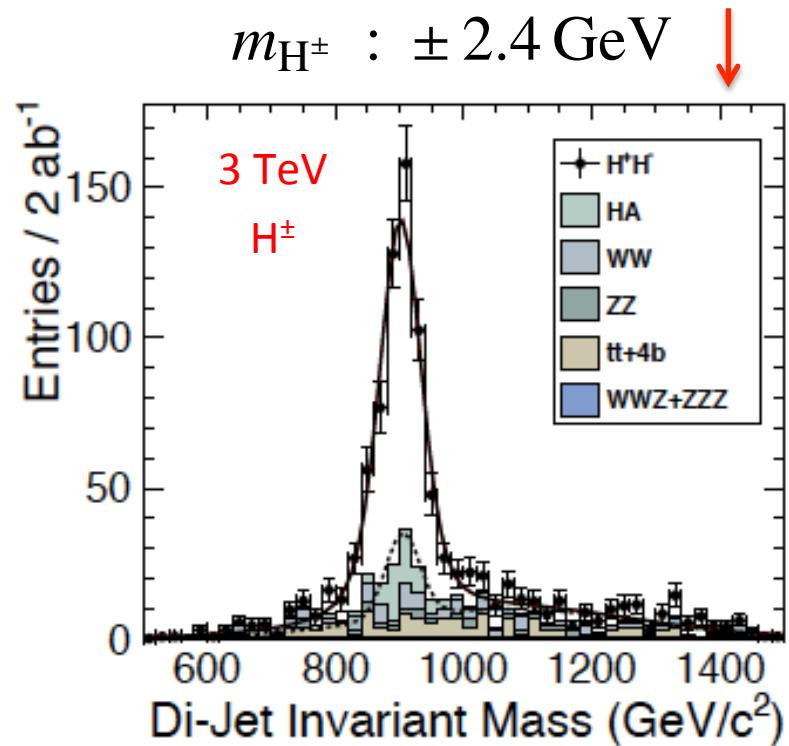
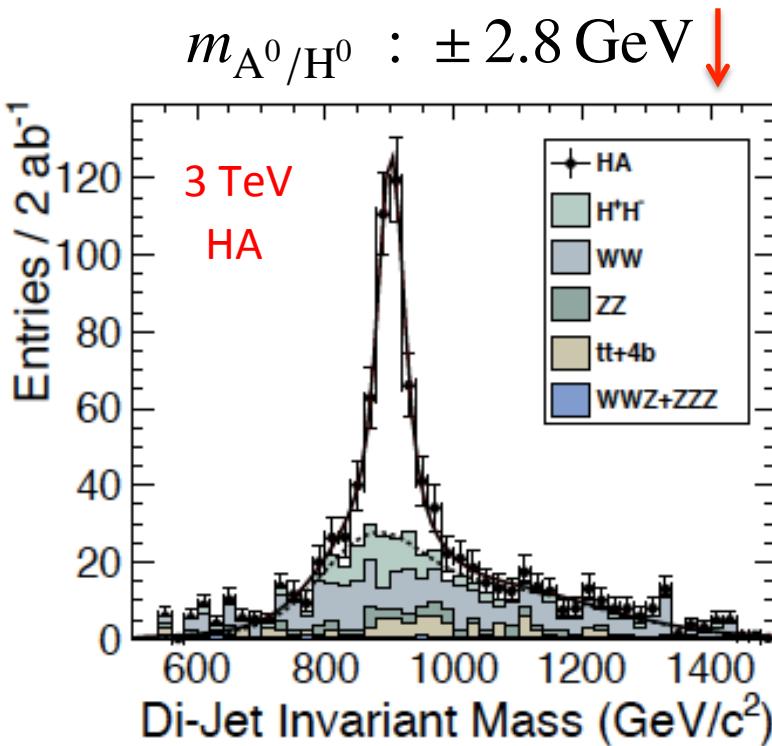
heavy Higgs, non-SM

Higgs multiplet BSM → searches accessible up to $\sqrt{s}/2$

Example MSSM benchmark study at 3 TeV

Multi-jet final states

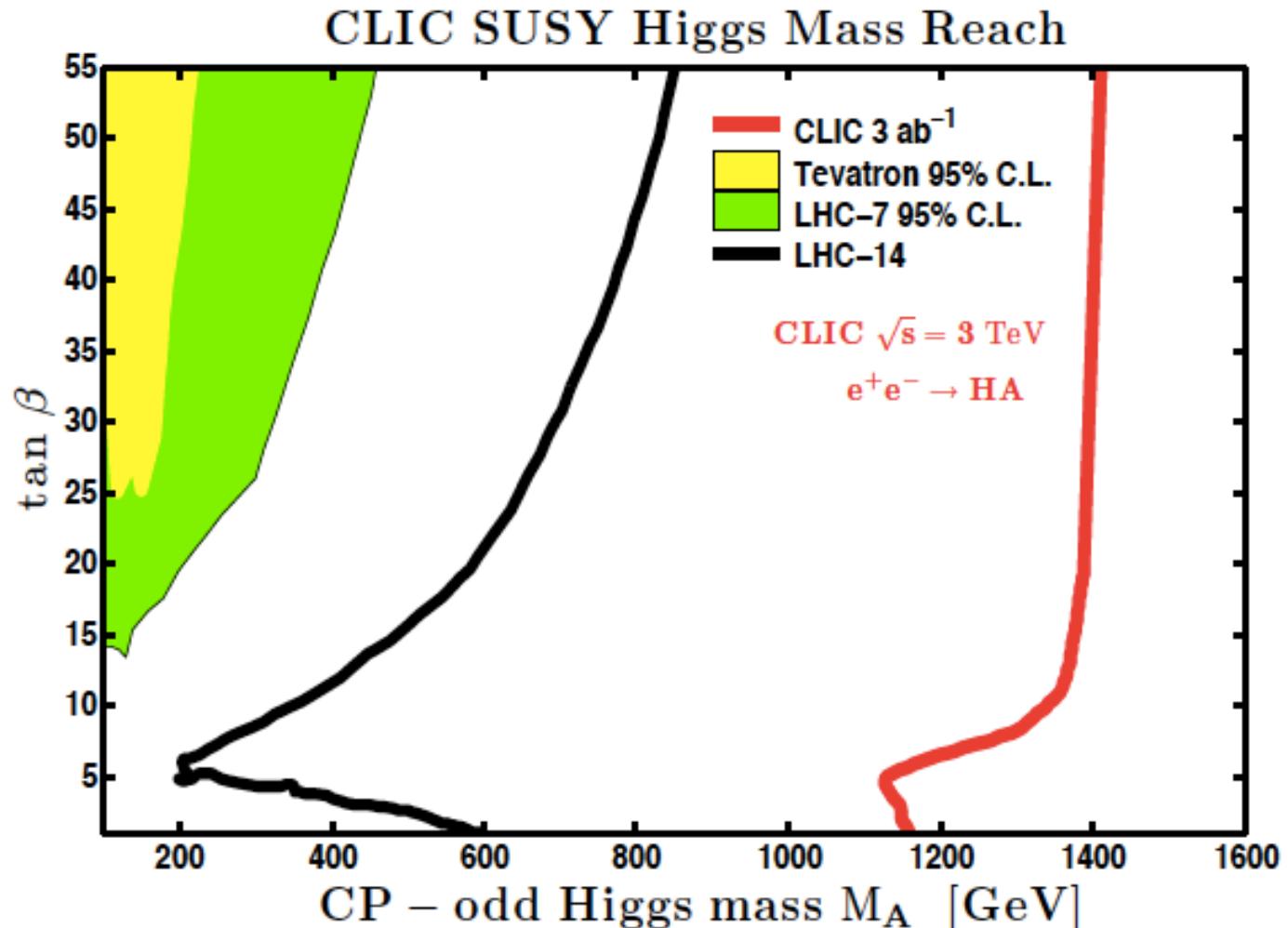
Full simulation studies with background overlay



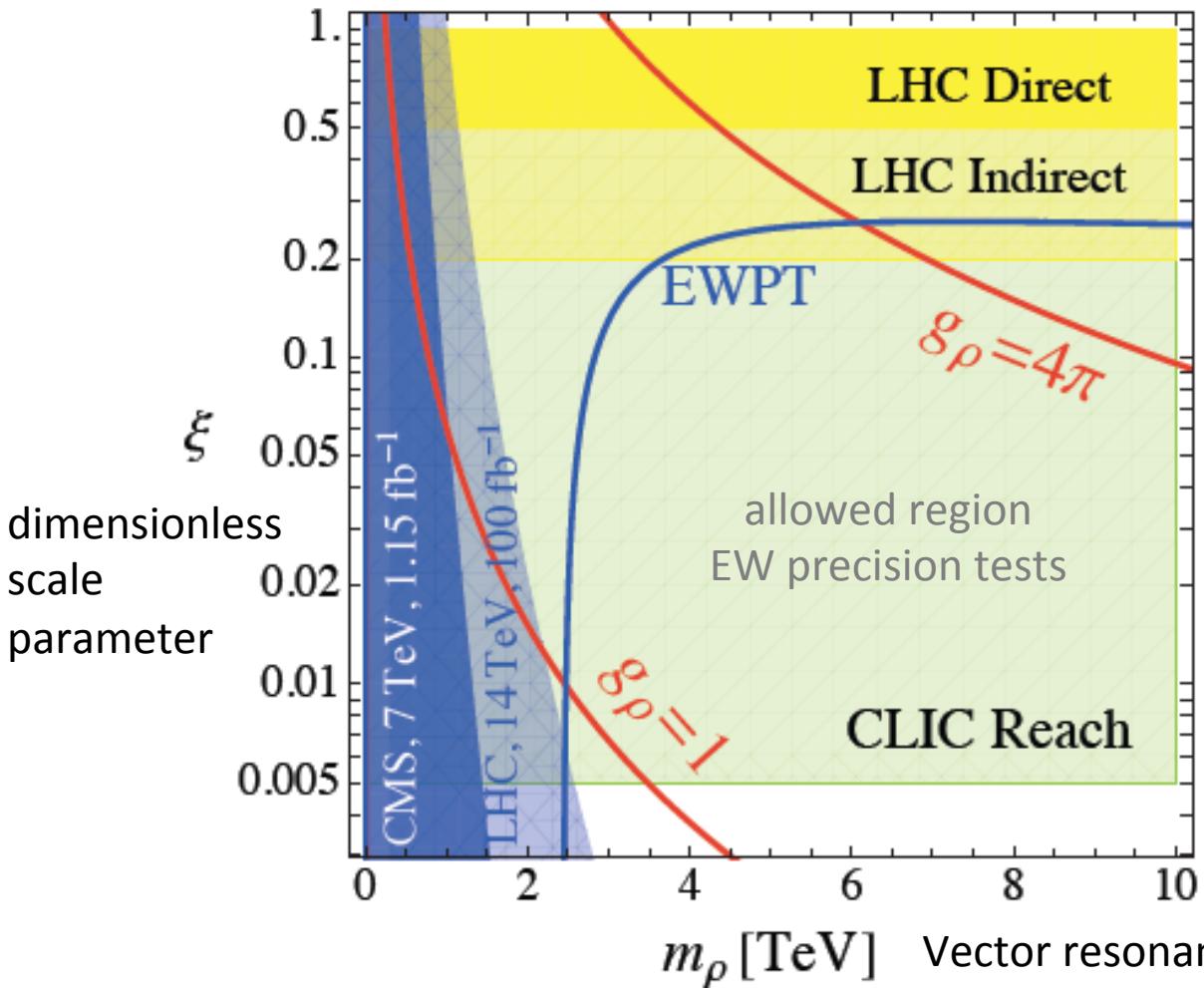
$$\begin{aligned} M_1 &= 780 \text{ GeV}, M_2 = 940 \text{ GeV}, M_3 = 540 \text{ GeV} \\ A_0 &= -750 \text{ GeV}, m_0 = 303 \text{ GeV}, \tan\beta = 24, \mu > 0 \\ m_t &= 173.3 \text{ GeV}, M_b(M_b) = 4.25 \text{ GeV}, \alpha_S(M_z) = 0.118 \end{aligned}$$

heavy Higgs searches

CLIC access to SUSY heavy Higgs searches



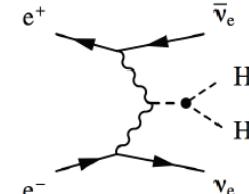
Higgs compositeness



LHC: WW scattering and strong double Higgs production

LHC: single Higgs processes

CLIC: double Higgs production via vector boson fusion



LHC: direct search $WZ \Rightarrow 3$ leptons

Allows to probe Higgs compositeness at the 30 TeV scale for 1 ab^{-1} at 3 TeV
(60 TeV scale if combined with single Higgs production)

SUSY => slepton study, 3 TeV



Slepton production at CLIC very clean

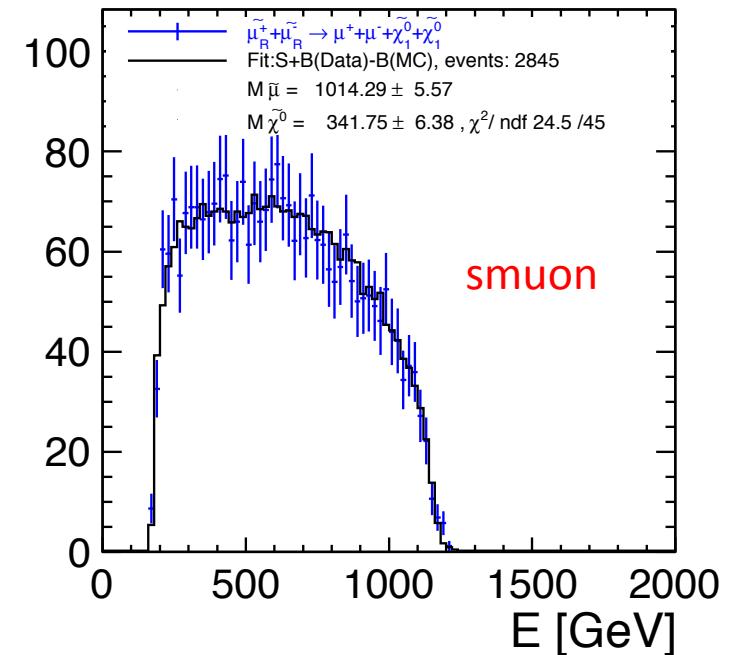
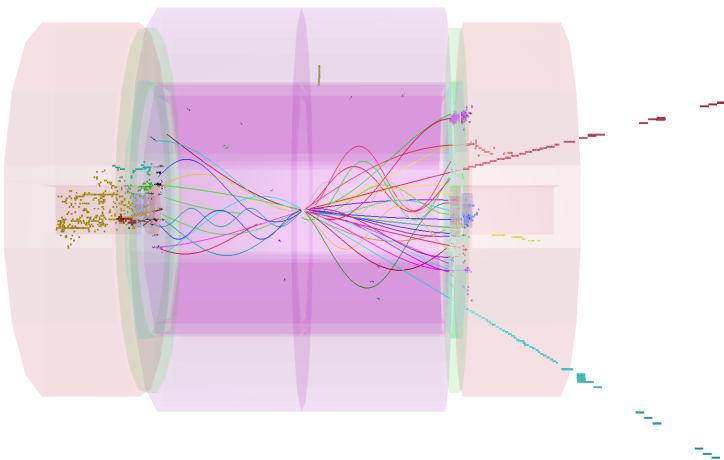
SUSY “model II”: slepton masses ~ 1 TeV

Channels studied include

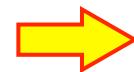
- $e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$
- $e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^- \rightarrow e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$
- $e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e \rightarrow e^+e^-W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$

Leptons and missing energy

Masses from analysis of endpoints of energy spectra



All channels combined



$m(\tilde{\mu}_R) : \pm 5.6$ GeV
$m(\tilde{e}_R) : \pm 2.8$ GeV
$m(\tilde{\nu}_e) : \pm 3.9$ GeV
$m(\tilde{\chi}_1^0) : \pm 3.0$ GeV
$m(\tilde{\chi}_1^\pm) : \pm 3.7$ GeV

gaugino pair production, 3 TeV



SUSY “model II”: $m(\tilde{\chi}_1^0) = 340 \text{ GeV}$ $m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 643 \text{ GeV}$

Pair production and decay:

$$e^+ e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$$

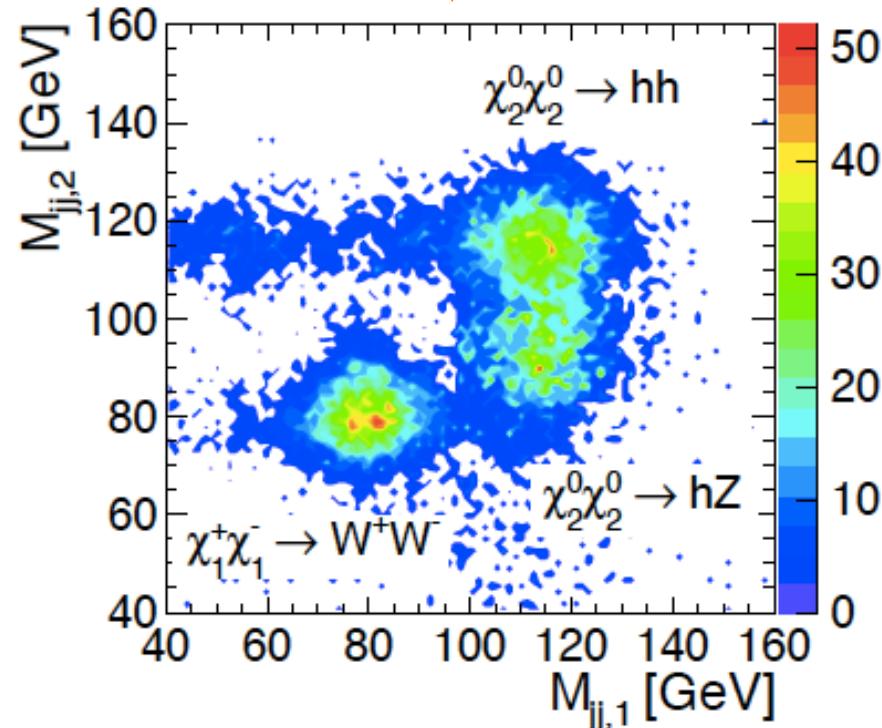
$$e^+ e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow hh \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 82\%$$

$$e^+ e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow Zh \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 17\%$$

Separation using di-jet invariant masses (test of PFA)

→ $m(\tilde{\chi}_1^\pm) : \pm 7 \text{ GeV}$
 $m(\tilde{\chi}_2^0) : \pm 10 \text{ GeV}$

→ use slepton study result
 $m(\tilde{\chi}_1^0) : \pm 3 \text{ GeV}$



results of SUSY benchmarks, 1.4 TeV



\sqrt{s} (TeV)	Process	Decay mode	SUSY model	Measured quantity	Unit	Gener- ator value	Stat. error	
1.4	Sleptons production	$\tilde{\mu}_R^+ \tilde{\mu}_R^- \rightarrow \mu^+ \mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$	III	σ	fb	1.11	2.7%	
				$\tilde{\ell}$ mass	GeV	560.8	0.1%	
				$\tilde{\chi}_1^0$ mass	GeV	357.8	0.1%	
	Sleptons production	$\tilde{e}_R^+ \tilde{e}_R^- \rightarrow e^+ e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$		σ	fb	5.7	1.1%	
				$\tilde{\ell}$ mass	GeV	558.1	0.1%	
				$\tilde{\chi}_1^0$ mass	GeV	357.1	0.1%	
1.4	Neutralino production	$\tilde{\nu}_e \tilde{\nu}_e \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 e^+ e^- W^+ W^-$		σ	fb	5.6	3.6%	
				$\tilde{\ell}$ mass	GeV	644.3	2.5%	
				$\tilde{\chi}_1^\pm$ mass	GeV	487.6	2.7%	
	Stau production	$\tilde{\tau}_1^+ \tilde{\tau}_1^- \rightarrow \tau^+ \tau^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$		$\tilde{\tau}_1$ mass	GeV	517	2.0%	
				σ	fb	2.4	7.5%	
1.4	Chargino production	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$	III	$\tilde{\chi}_1^\pm$ mass	GeV	487	0.2%	
				σ	fb	15.3	1.3%	
	Neutralino production	$\tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow h/Z^0 h/Z^0 \tilde{\chi}_1^0 \tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	GeV	487	0.1%	
				σ	fb	5.4	1.2%	

all results
with
 $L \Rightarrow 1.5$
 ab^{-1}

CLIC CDR
Vol. 3

Large part of the SUSY spectrum measured at <1% level

results of SUSY benchmarks, 3 TeV

\sqrt{s} (TeV)	Process	Decay mode	SUSY model	Measured quantity	Unit	Gener- ator value	Stat. error	
3.0	Sleptons production	$\tilde{\mu}_R^+ \tilde{\mu}_R^- \rightarrow \mu^+ \mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$	II	σ	fb	0.72	2.8%	
				$\tilde{\ell}$ mass	GeV	1010.8	0.6%	
				$\tilde{\chi}_1^0$ mass	GeV	340.3	1.9%	
		$\tilde{e}_R^+ \tilde{e}_R^- \rightarrow e^+ e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$		σ	fb	6.05	0.8%	
				$\tilde{\ell}$ mass	GeV	1010.8	0.3%	
	Chargino production	$\tilde{e}_L^+ \tilde{e}_L^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 e^+ e^- hh$		$\tilde{\chi}_1^0$ mass	GeV	340.3	1.0%	
				σ	fb	3.07	7.2%	
		$\tilde{v}_e \tilde{v}_e \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 e^+ e^- W^+ W^-$		σ	fb	13.74	2.4%	
				$\tilde{\ell}$ mass	GeV	1097.2	0.4%	
				$\tilde{\chi}_1^\pm$ mass	GeV	643.2	0.6%	
3.0	Neutralino production	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$	II	$\tilde{\chi}_1^\pm$ mass	GeV	643.2	1.1%	
		$\tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow h/Z^0 h/Z^0 \tilde{\chi}_1^0 \tilde{\chi}_1^0$		σ	fb	10.6	2.4%	
	Production of right-handed squarks	$\tilde{q}_R \tilde{q}_R \rightarrow q \bar{q} \tilde{\chi}_1^0 \tilde{\chi}_1^0$		$\tilde{\chi}_2^0$ mass	GeV	643.1	1.5%	
				σ	fb	3.3	3.2%	
3.0	Heavy Higgs production	$H^0 A^0 \rightarrow b \bar{b} b \bar{b}$	I	Mass	GeV	1123.7	0.52%	
		$H^+ H^- \rightarrow t \bar{b} b \bar{t}$		σ	fb	1.47	4.6%	
		$H^0 A^0 \rightarrow b \bar{b} b \bar{b}$	I	Mass	GeV	902.4	0.3%	
				Width	GeV		31%	
				Mass	GeV	906.3	0.3%	
				Width	GeV		27%	

all results
with
 $L = 2 \text{ ab}^{-1}$

CLIC CDR
Vol. 2

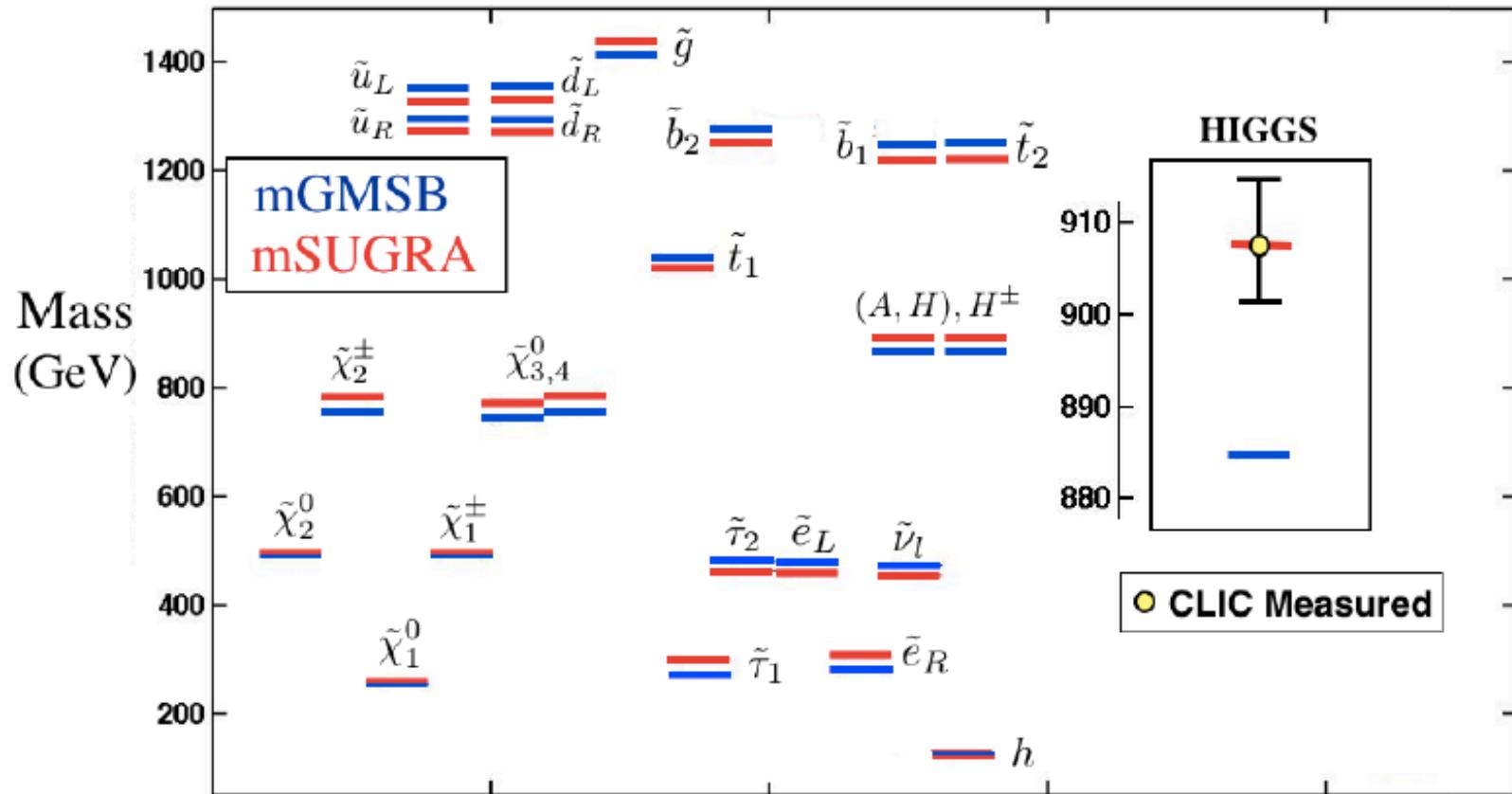
Large part of the SUSY spectrum measured at <1% level

resolving new physics models



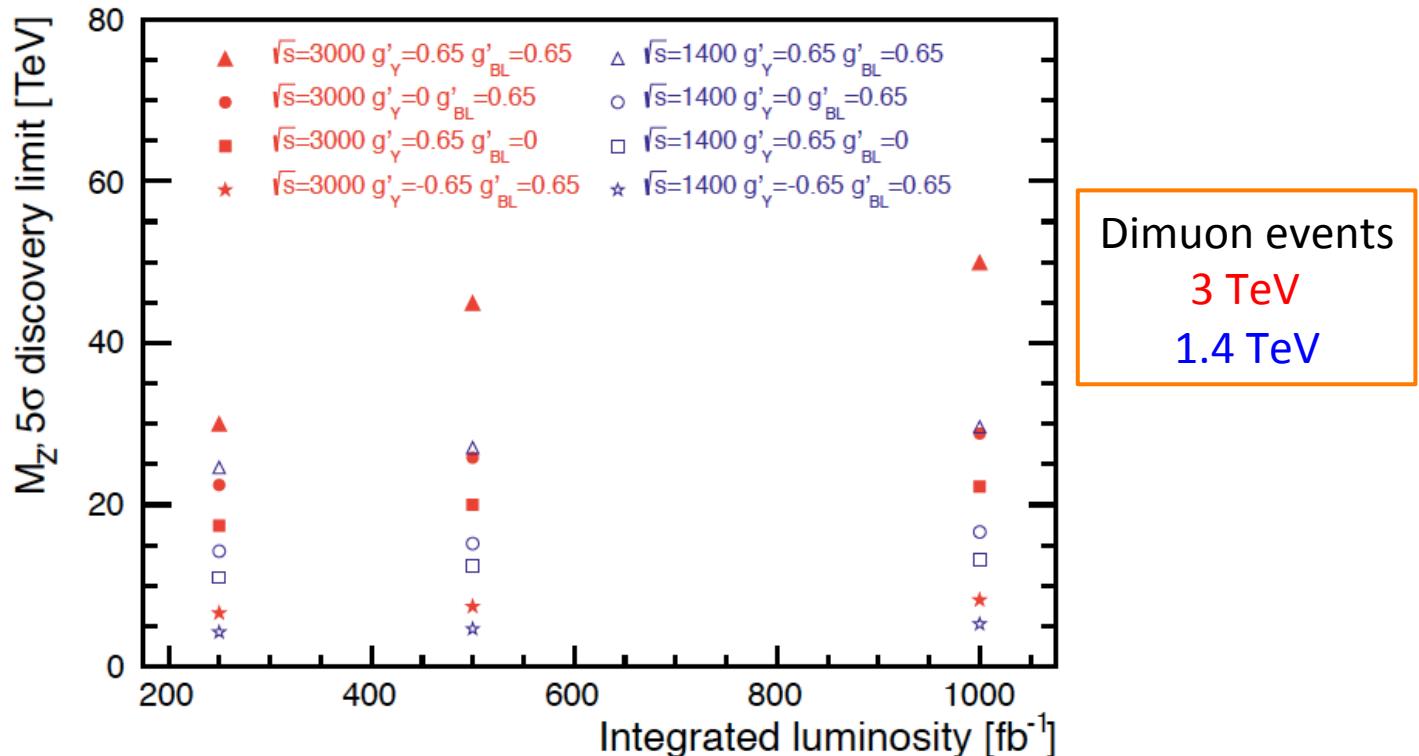
Precision measurements at CLIC allow to distinguish between models of new physics, e.g. following first observations at LHC

e.g. CLIC 3 TeV example, resolving power for SUSY breaking models



sensitivity to Z'

Example: neutral gauge boson (Z') in minimal anomaly-free Z' model (AFZ')



$M_{Z'}$ 5σ discovery limit as function of the integrated luminosity for different values of the couplings g'_Y and g'_{BL} . The limits shown are determined from the combined observables σ + A_{FB} at 3 TeV and 1.4 TeV.

Study of Z' 5σ discovery potential in at 1.4 TeV and 3 TeV, for different coupling values

contact interactions

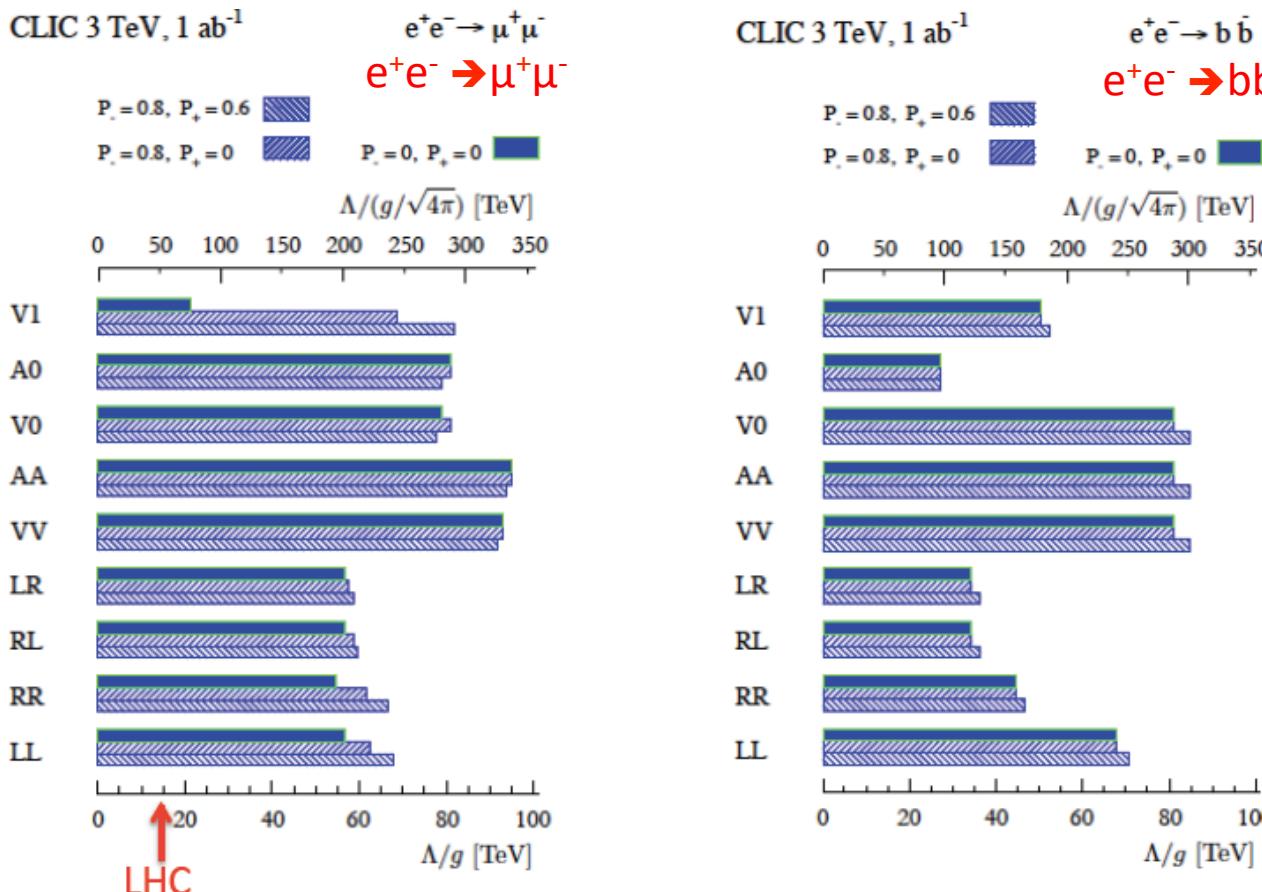


Fig. 1.14: Limits on the scale of contact interactions (Λ/g) that can be set by CLIC in the $\mu^+\mu^-$ (left) and $b\bar{b}$ (right) channels with $\sqrt{s} = 3 \text{ TeV}$ and $\mathcal{L} = 1 \text{ ab}^{-1}$. A degree of polarisation $P_- = 0, 0.8$ ($P_+ = 0, 0.6$) has been assumed for the electrons (positrons). The various models are defined in Table 6.6 of [20], except the model V1 which is defined as $\{\eta_{LL} = \pm, \eta_{RR} = \mp, \eta_{LR} = 0, \eta_{RL} = 0\}$.

22

Limits on the scale (Λ/g) of contact interactions

CLIC physics reach, short overview

Have just scratched the surface of CLIC physics

- more details given in Vol. 2 & 3 of CLIC CDR

Challenge the Standard Model with **direct measurements** and at the **loop level**

- Challenge SM up to the 60 TeV scale

New particle	CLIC3 1 ab ⁻¹	
squarks [TeV]	1.5	
sleptons [TeV]	1.5	
Z' (SM couplings) [TeV]	20	
2 extra dims M_D [TeV]	20-30	
TGC (95%) (λ_γ coupling)	0.0001	
μ contact scale [TeV]	60	
Higgs compos. scale [TeV]	60	

CLIC
3 TeV

} Direct observation

} Loop /
effective operator

CLIC detector and physics study organisation

Pre-collaboration structure, based on a “Memorandum on Cooperation”
<http://lcd.web.cern.ch/LCD/Home/MoC.html>



Australia: ACAS; Belarus: NC PHEP Minsk; Czech Republic: Academy of Sciences Prague; Denmark: Aarhus Univ.; Germany: MPI Munich; Israel: Tel Aviv Univ.; Norway: Bergen Univ.; Poland: Cracow AGH + Cracow Niewodniczanski Inst.; Romania: Inst. of Space Science; Serbia: Vinca Inst. Belgrade; Spain: Spanish LC network; UK: Birmingham Univ. + Cambridge Univ. + Oxford Univ.; USA: Argonne lab; + CERN

summary and outlook

CLIC Physics:

- Complementary to the LHC
- Focus on high precision measurements
- Physics reach demonstrated (full simulation with pile-up)
- Staged approach => large potential for SM and BSM physics

~350 – 375 GeV : precision Higgs and top physics

~1.5 TeV : Higgs (including ttH and self-coupling), BSM

~3 TeV : Higgs, Higgs self-coupling, BSM, ...

Ongoing CLIC physics potential studies

- current focus on detailed Higgs studies
- more on BSM on a ≥ 1 year timescale

**CLIC is an exciting and realistic option for
a future machine at the energy frontier**

Welcome to join !

lcd.web.cern.ch/lcd/

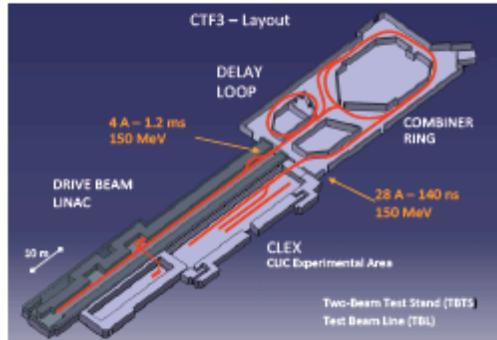
SPARE SLIDES

CLIC strategy and objectives



2012-16 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.



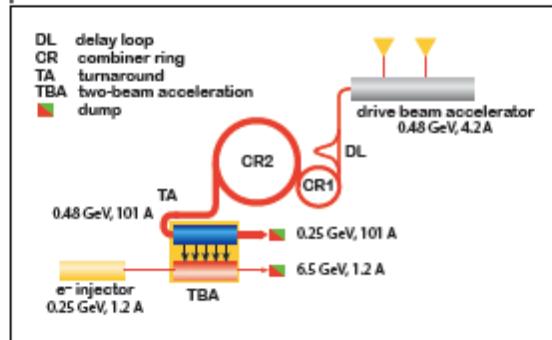
2016-17 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

2017-22 Preparation Phase

Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

Prepare detailed Technical Proposals for the detector-systems.



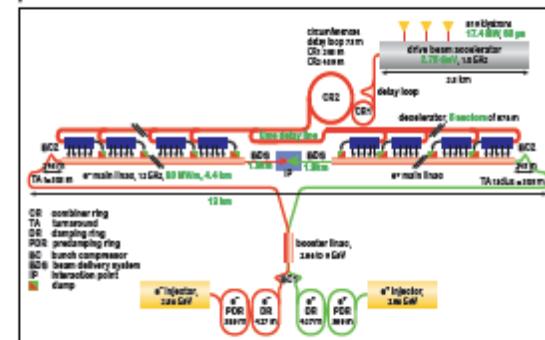
2022-23 Construction Start

Ready for full construction and main tunnel excavation.

2023-2030 Construction Phase

Stage 1 construction of a 500 GeV CLIC, in parallel with detector construction.

Preparation for implementation of further stages.



2030 Commissioning

From 2030, becoming ready for data-taking as the LHC programme reaches completion.

Faster implementation possible, (e.g. for lower-energy Higgs factory): klystron-based initial stage

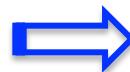
plans for the phase 2013-2016



Further exploration of the physics potential

- Complete picture of Higgs prospects at ~350 GeV, ~1.4 TeV, ~3 TeV
- Discovery reach for BSM physics
- Sensitivity to BSM through high-precision measurements

cf. LHC
results



Drives the CLIC staging strategy

Detector Optimisation studies

- Optimisation studies linked to physics (e.g aspect ratio, forward region coverage);
- Interplay between occupancies and reconstruction;
- Interplay between technology R&D and simulation models.

Technology demonstrators

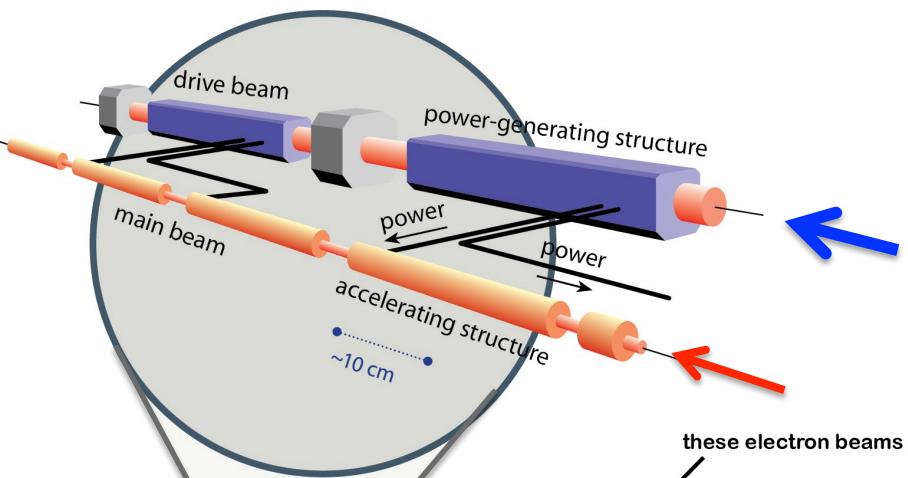
- Many common developments with ILC
- Complemented with CLIC requirements



CLIC two-beam acceleration scheme



Accelerating gradient: 100 MV/m



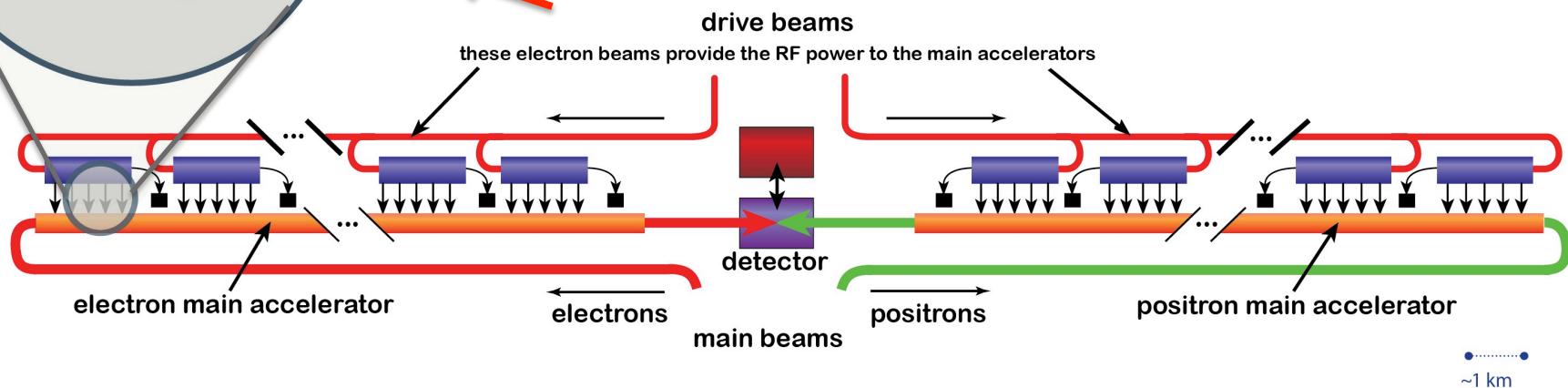
Two Beam Scheme:

Drive Beam supplies RF power

- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam for physics

- high energy (9 GeV – 1.5 TeV)
- current 1.2 A



CLIC layout at 3 TeV

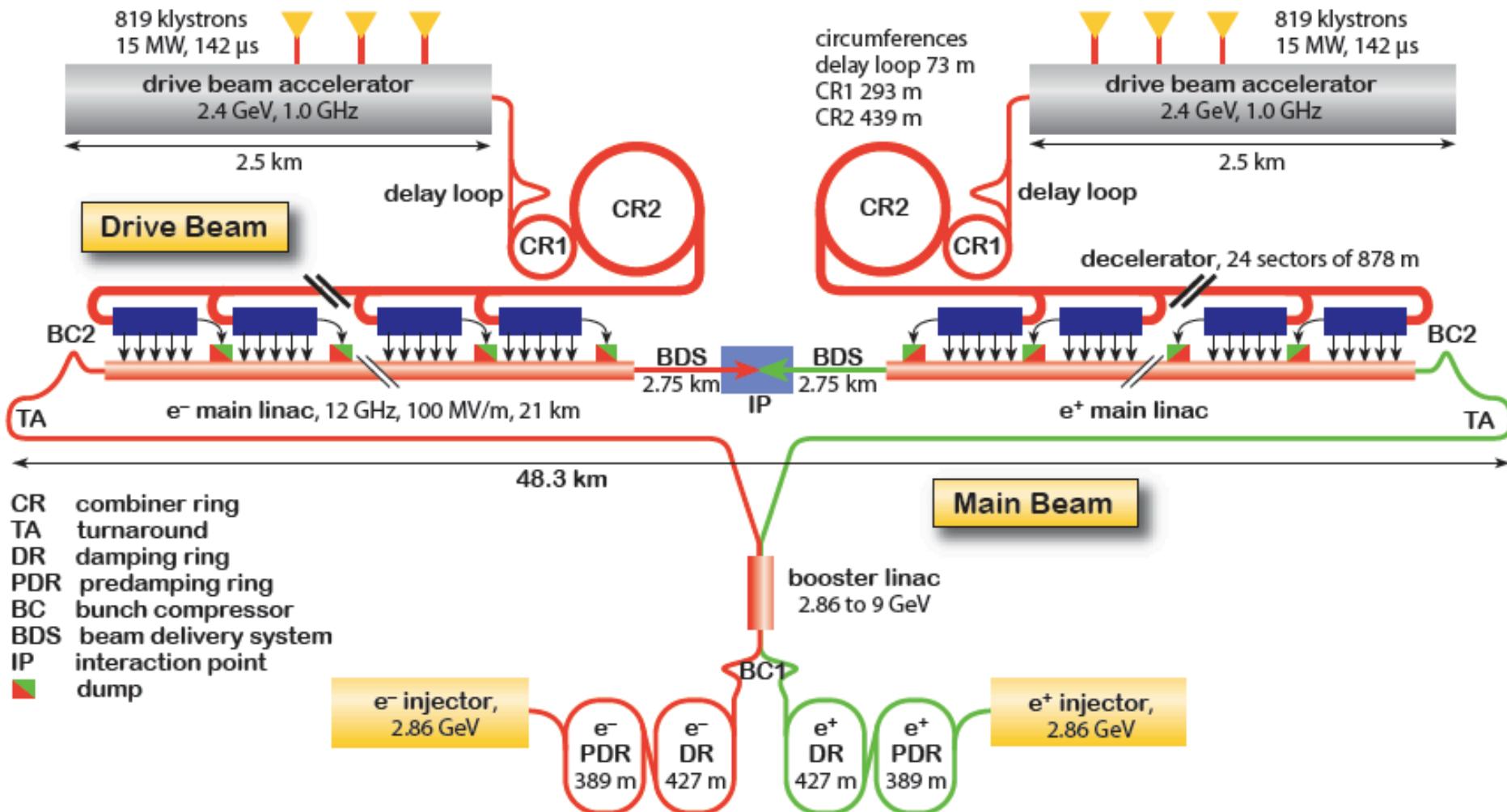


Fig. 3.1: Overview of the CLIC layout at $\sqrt{s} = 3$ TeV.

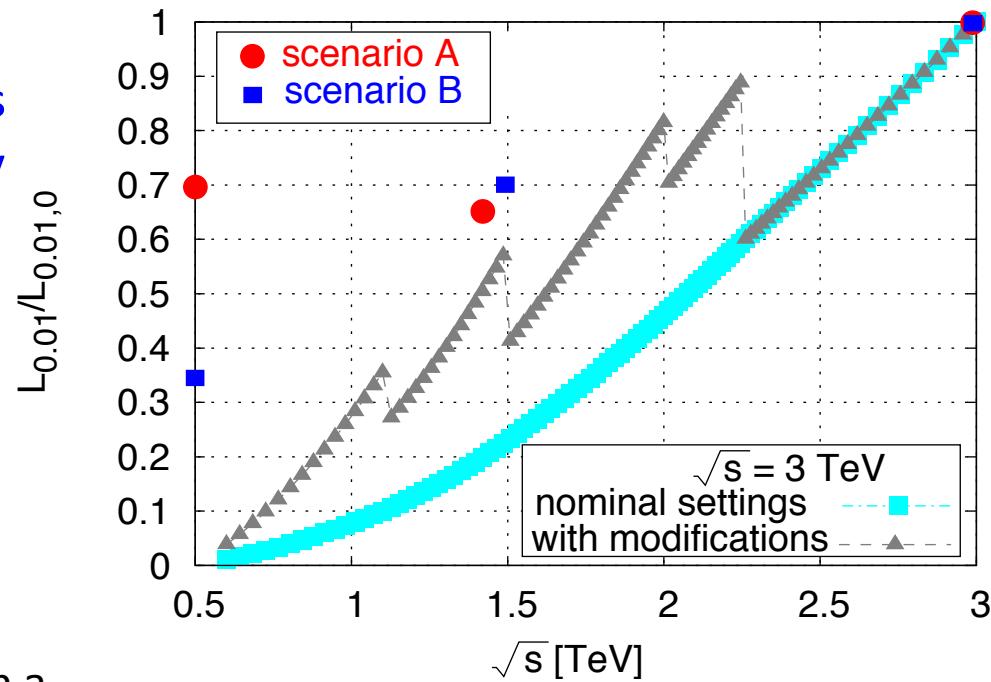
motivation for energy staging

CLIC physics potential:

- Good physics at various CM energies
- Most studies require high luminosity

At each energy stage, the centre-of-mass energy can be tuned down by a factor ~ 3 with limited luminosity loss (e.g. for threshold scans)

Making optimal use of the capacities (luminosity) of CLIC, this is best studied with a **collider built in a few successive energy stages.**



The optimal choice of the actual energy stages will depend on the physics scenario, driven by 8 TeV + 14 TeV LHC results.

The scenarios “A” and “B” are therefore “**just examples**”

Parameters, scenario A



Table 3.3: Parameters for the CLIC energy stages of scenario A.

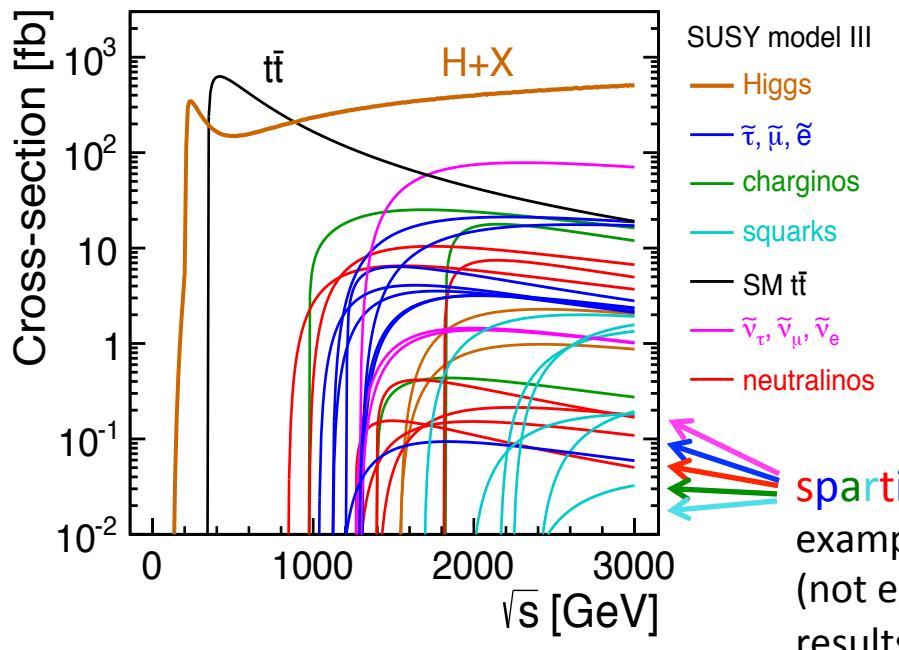
Parameter	Symbol	Unit			
Centre-of-mass energy	\sqrt{s}	GeV	500	1400	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		354	312	312
Bunch separation	Δ_t	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	80	80/100	100
Total luminosity	\mathcal{L}	$10^{34} \text{ cm}^{-2}\text{s}^{-1}$	2.3	3.2	5.9
Luminosity above 99% of \sqrt{s}	$\mathcal{L}_{0.01}$	$10^{34} \text{ cm}^{-2}\text{s}^{-1}$	1.4	1.3	2
Main tunnel length		km	13.2	27.2	48.3
Charge per bunch	N	10^9	6.8	3.7	3.7
Bunch length	σ_z	μm	72	44	44
IP beam size	σ_x/σ_y	nm	200/2.6	$\approx 60/1.5$	$\approx 40/1$
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	2350/20	660/20	660/20
Normalised emittance (IP)	ϵ_x/ϵ_y	nm	2400/25	—	—
Estimated power consumption	P_{wall}	MW	272	364	589

Parameters, scenario B

Table 3.4: Parameters for the CLIC energy stages of scenario B.

Parameter	Symbol	Unit			
Centre-of-mass energy	\sqrt{s}	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δ_t	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	\mathcal{L}	$10^{34} \text{ cm}^{-2}\text{s}^{-1}$	1.3	3.7	5.9
Luminosity above 99% of \sqrt{s}	$\mathcal{L}_{0.01}$	$10^{34} \text{ cm}^{-2}\text{s}^{-1}$	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	μm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	$\approx 60/1.5$	$\approx 40/1$
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	—	660/20	660/20
Normalised emittance	ϵ_x/ϵ_y	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589

SUSY model for 1.4 TeV studies



$M_1 = 840 \text{ GeV}, M_2 = 600 \text{ GeV}, M_3 = 450 \text{ GeV}$
 $A_0 = -800 \text{ GeV}, \tan \beta = 20$
 $\mu = +902 \text{ GeV}, m_{A^0, \text{pole}} = 765 \text{ GeV}$
 $m_{\tilde{Q}_{1,2}} = m_{\tilde{u}_{1,2}} = m_{\tilde{d}_{1,2}} = 2000 \text{ GeV}$
 $m_{\tilde{Q}_3} = m_{\tilde{u}_3} = m_{\tilde{d}_3} = 900 \text{ GeV}$
 $m_{\tilde{L}_{1,2,3}} = m_{\tilde{e}_{1,2,3}} = 500 \text{ GeV}$

model parameters

masses
(GeV)

Neutralinos ($\tilde{\chi}_{1,2,3,4}^0$) :	357, 487, 904, 911
Charginos ($\tilde{\chi}_{1,2}^\pm$) :	487, 911
Sleptons ($\tilde{e}_R, \tilde{e}_L, \tilde{v}_e$) :	559, 650, 644
$(\tilde{\tau}_1, \tilde{\tau}_2, \tilde{v}_\tau)$:	517, 642, 630
Gluino (\tilde{g}) :	1114
Squarks ($\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$) :	844, 1120, 1078, 1191
$(\tilde{d}_R, \tilde{u}_R, \tilde{d}_L, \tilde{u}_L)$:	2167, 2181, 2197, 2196
Higgs Bosons (h^0, A^0, H^0, H^\pm) :	118, 765, 765, 769

physics aims => detector needs

★ momentum resolution:

e.g. Smuon endpoint

Higgs recoil mass, Higgs coupling to muons

$$\sigma_{p_T}/p_T^2 \sim 2 \times 10^{-5} \text{ GeV}^{-1}$$

★ jet energy resolution:

e.g. W/Z/h di-jet mass separation

$$\frac{\sigma_E}{E} \sim 3.5 - 5 \%$$

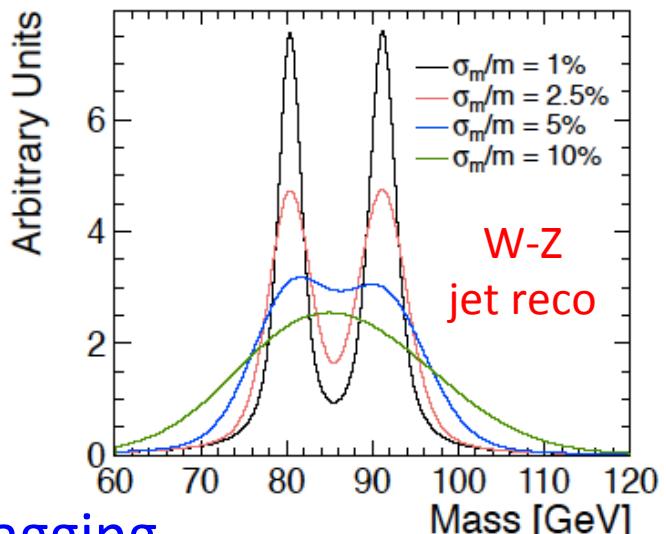
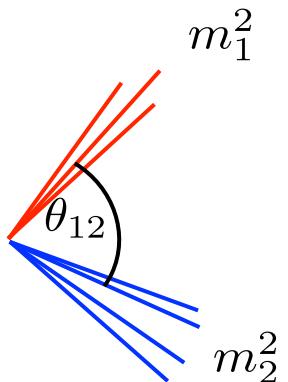
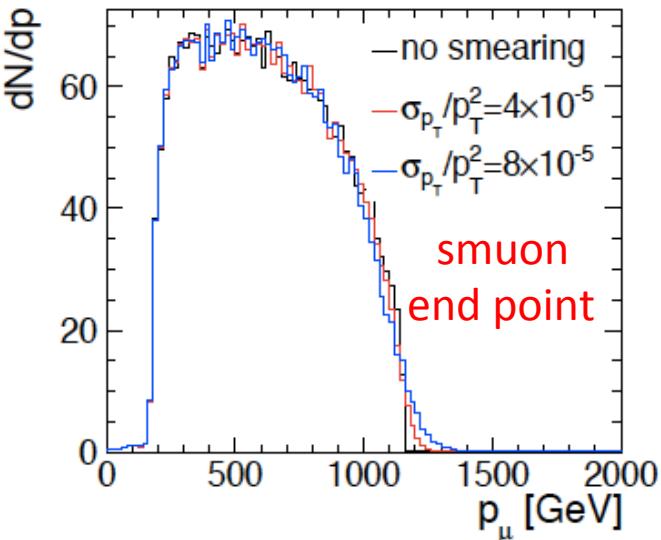
(for high-
E jets)

★ impact parameter resolution:

e.g. c/b-tagging, Higgs BR

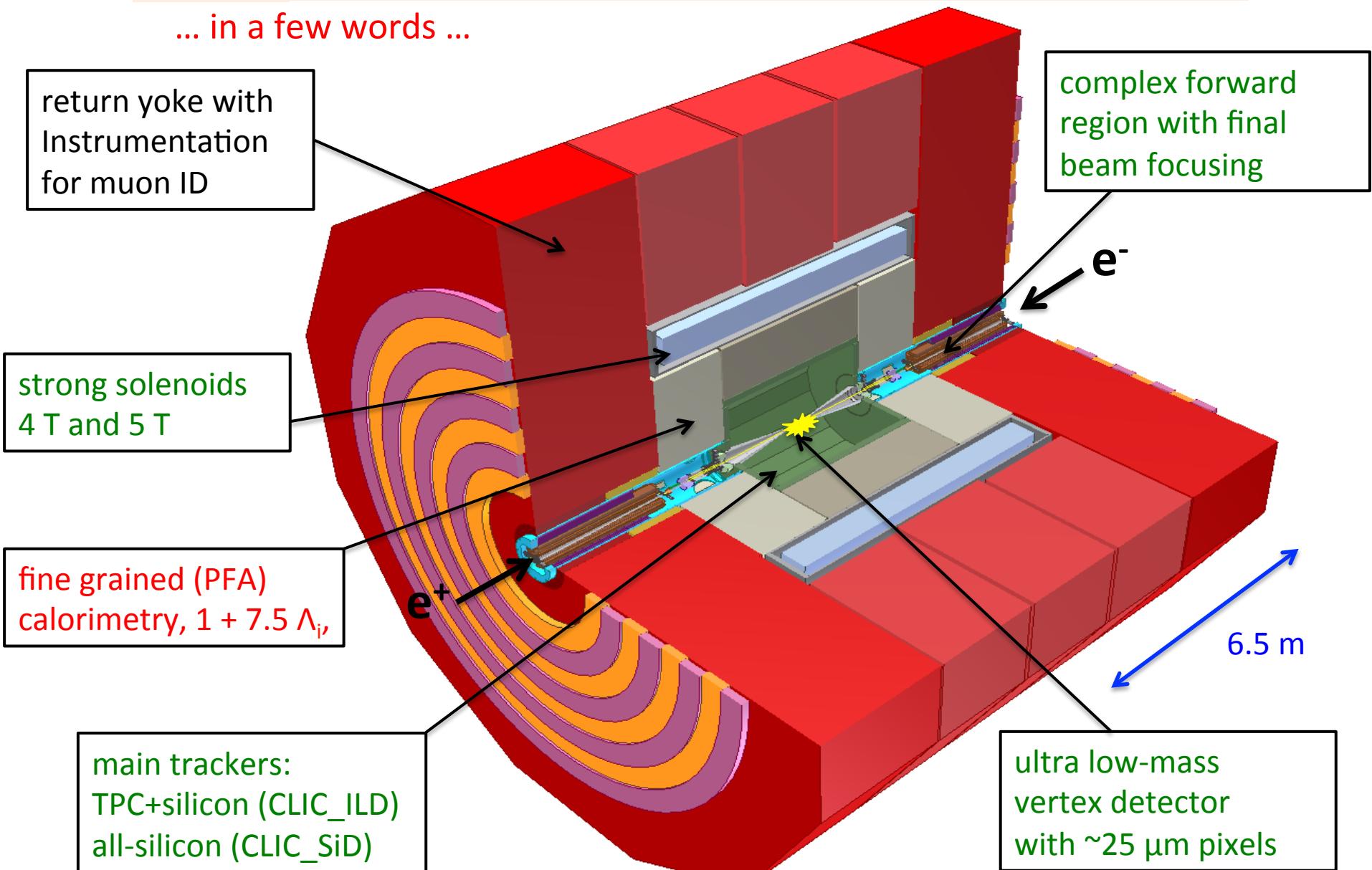
$$\sigma_{r\phi} = 5 \oplus 15/(p[\text{GeV}] \sin^{\frac{3}{2}} \theta) \mu\text{m}$$

★ angular coverage, very forward electron tagging



CLIC detector concepts

... in a few words ...



calorimetry and PFA

Jet energy resolution and background rejection drive the overall detector design
=> fine-grained calorimetry + Particle Flow Analysis (PFA)

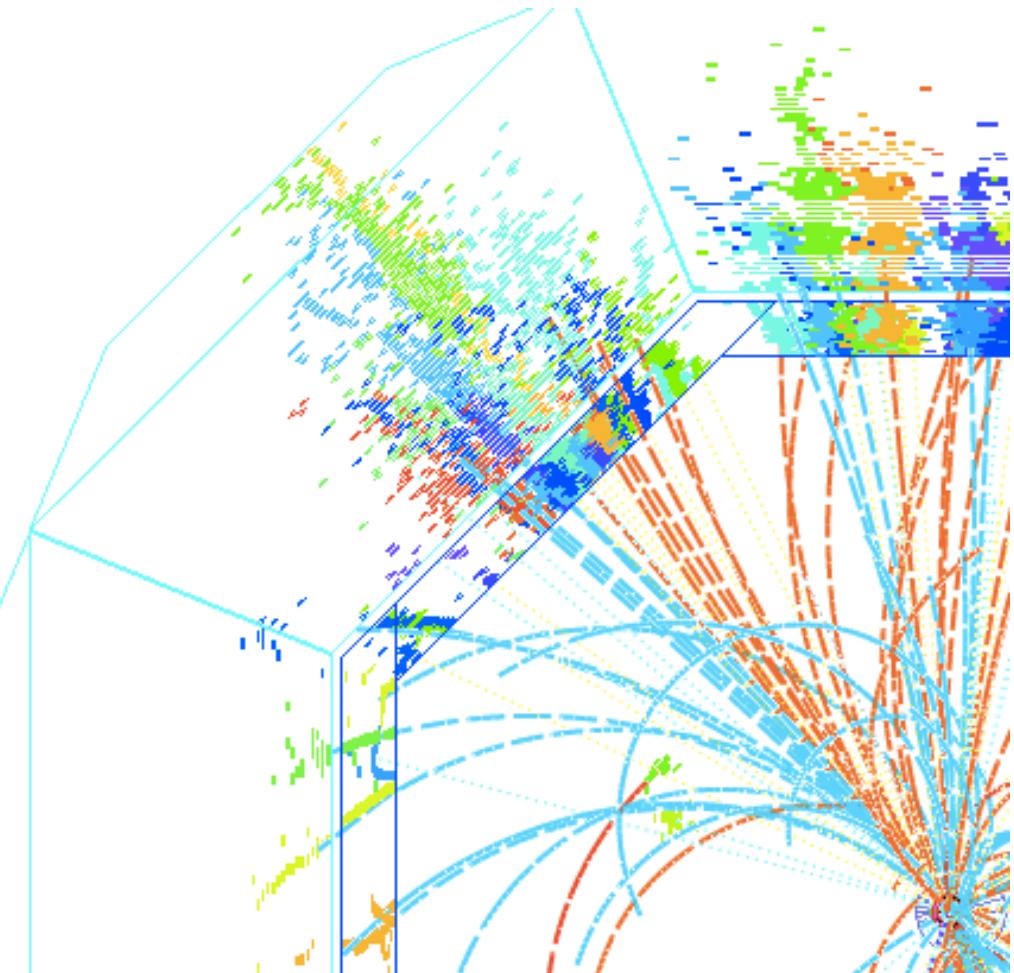
What is PFA?

Typical jet composition:
60% charged particles
30% photons
10% neutrons

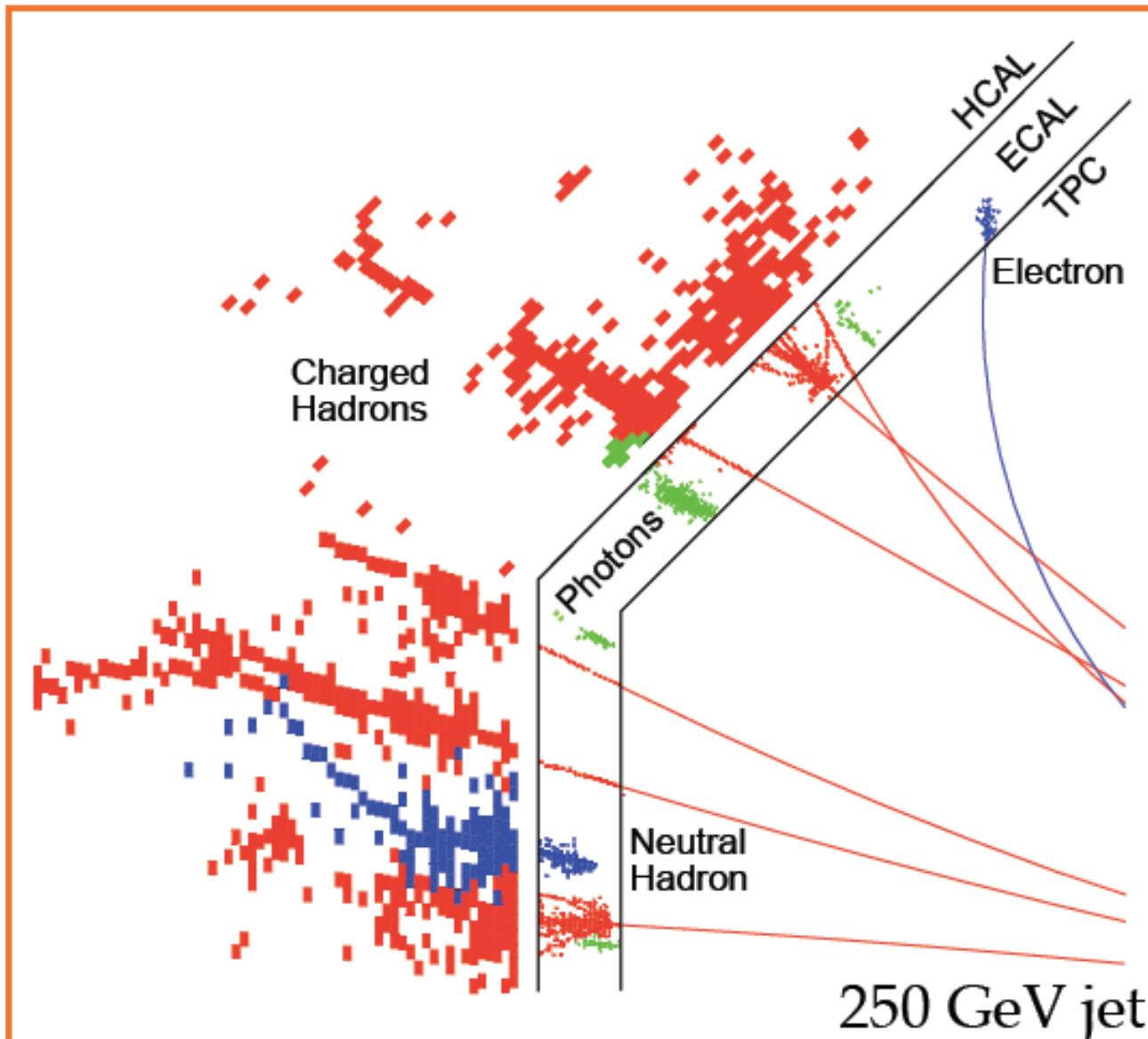


Always use the best info you have:
60% => tracker 😊 😊
30% => ECAL 😊
10% => HCAL 😞

Hardware + software !



calorimetry and PFA



CLIC machine environment (1)



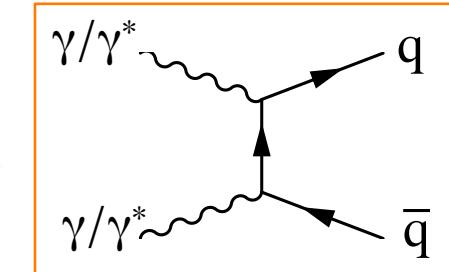
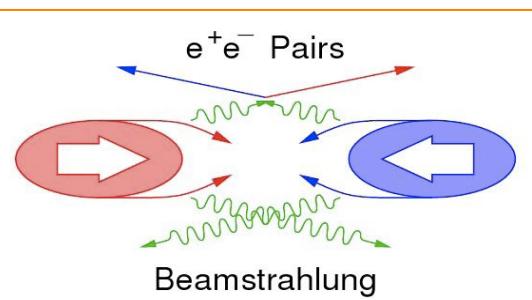
	CLIC at 3 TeV
$L (\text{cm}^{-2}\text{s}^{-1})$	5.9×10^{34}
BX separation	0.5 ns
#BX / train	312
Train duration (ns)	156
Rep. rate	50 Hz
$\sigma_x / \sigma_y (\text{nm})$	$\approx 45 / 1$
$\sigma_z (\mu\text{m})$	44

Drives timing requirements for CLIC detector

very small beam size

Beam related background:

- Small beam profile at IP leads very high E-field
- ◆ Beamstrahlung
 - ◆ Pair-background
 - ◆ $\gamma\gamma$ to hadrons



CLIC machine environment (2)



Coherent e^+e^- pairs

- ◆ 7×10^8 per BX, very forward

Incoherent e^+e^- pairs

- ◆ 3×10^5 per BX, rather forward

$\gamma\gamma \rightarrow \text{hadrons}$

- ◆ 3.2 events per BX
- ◆ main background in calorimeters
- ◆ $\sim 19 \text{ TeV}$ in HCAL per bunch train



Simplified view:

Pair background

- Design issue (high occupancies)
- $\gamma\gamma \rightarrow \text{hadrons}$
- Impacts on the physics
- Needs suppression in data

Beamstrahlung → important energy losses
right at the interaction point

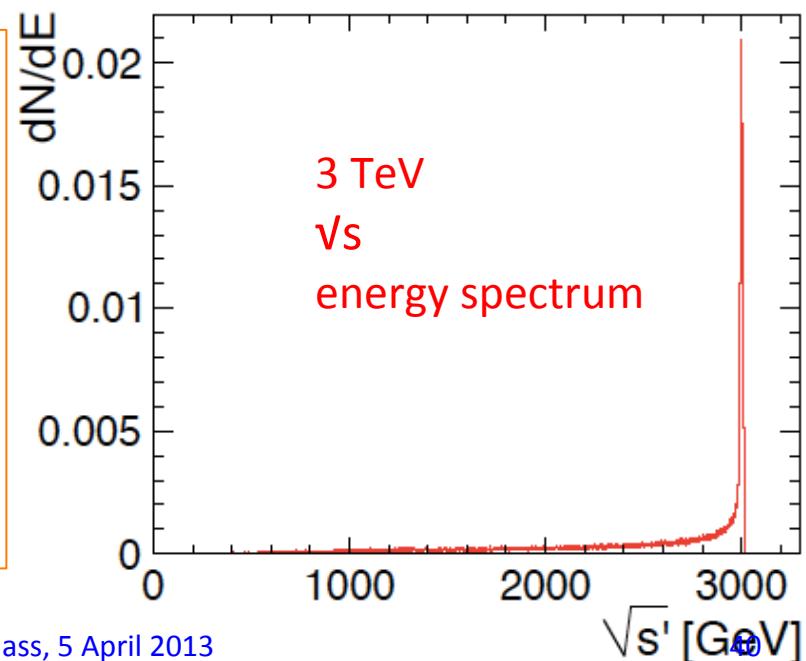
E.g. full luminosity at 3 TeV:

$$5.9 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

Of which in the 1% most energetic part:

$$2.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$$

Most physics processes are studied well above
production threshold => profit from full luminosity



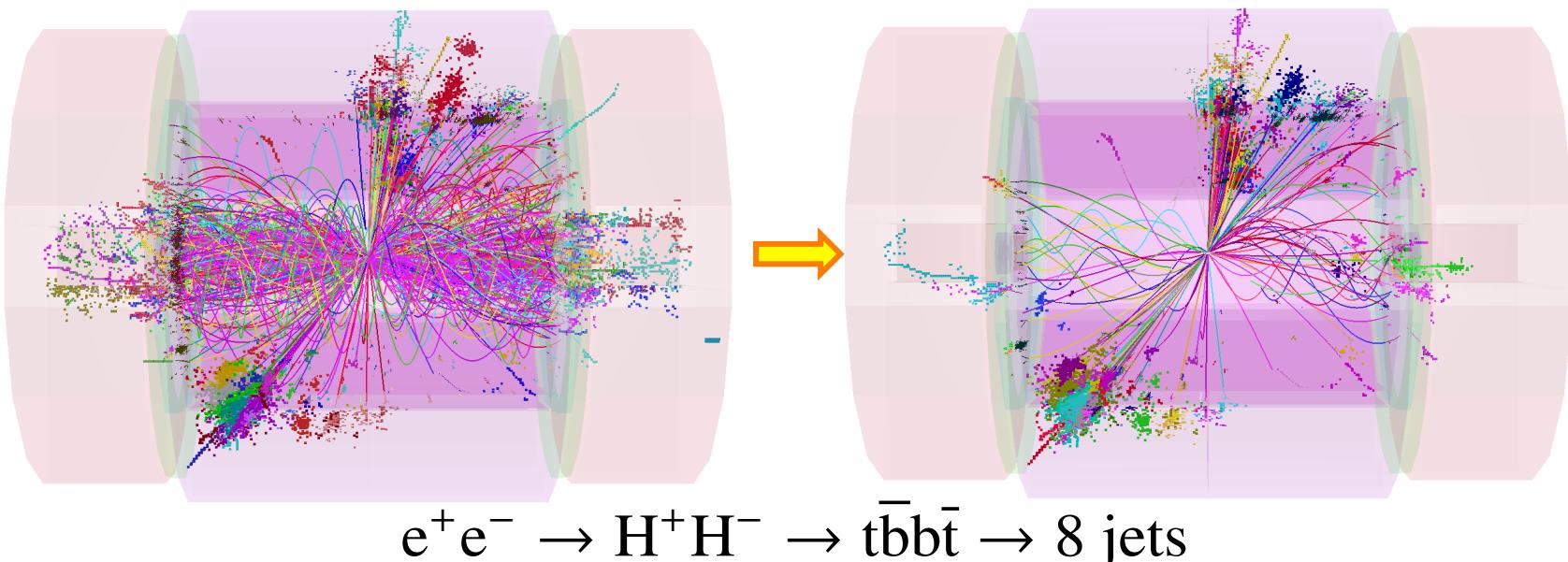
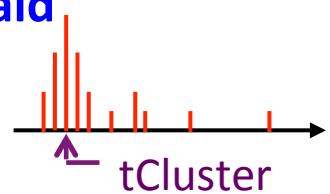
background suppression at CLIC



Triggerless readout of full train

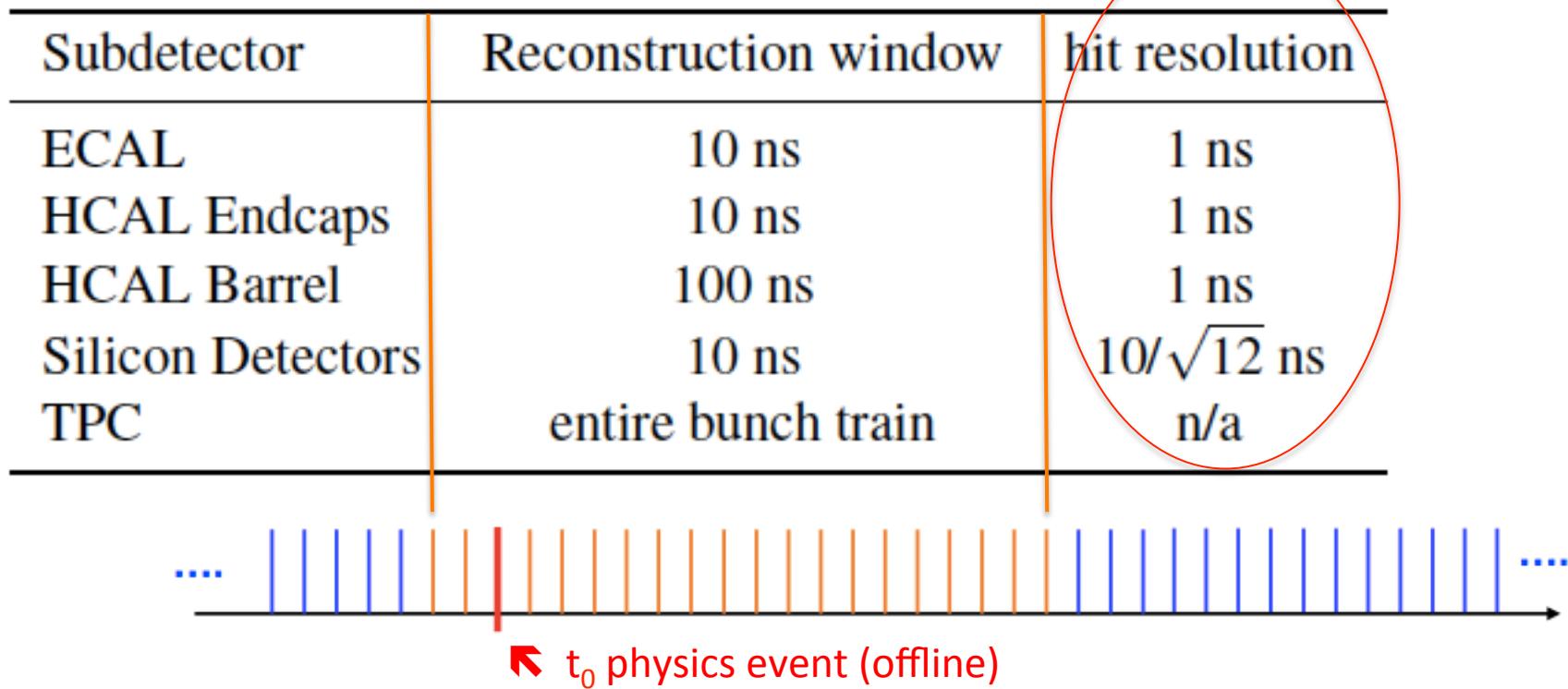


- Full event reconstruction + PFA analysis with background overlaid
 - => physics objects with precise p_T and cluster time information
- Then apply cluster-based timing cuts



time window / time resolution

The event reconstruction software uses:



Translates in precise **timing requirements** of the sub-detectors

PFO-based timing cuts

<i>Region</i>	p_t range	Time cut
Photons		
central $(\cos \theta \leq 0.975)$	$0.75 \text{ GeV} \leq p_t < 4.0 \text{ GeV}$	$t < 2.0 \text{ nsec}$
	$0 \text{ GeV} \leq p_t < 0.75 \text{ GeV}$	$t < 1.0 \text{ nsec}$
forward $(\cos \theta > 0.975)$	$0.75 \text{ GeV} \leq p_t < 4.0 \text{ GeV}$	$t < 2.0 \text{ nsec}$
	$0 \text{ GeV} \leq p_t < 0.75 \text{ GeV}$	$t < 1.0 \text{ nsec}$
Neutral hadrons		
central $(\cos \theta \leq 0.975)$	$0.75 \text{ GeV} \leq p_t < 8.0 \text{ GeV}$	$t < 2.5 \text{ nsec}$
	$0 \text{ GeV} \leq p_t < 0.75 \text{ GeV}$	$t < 1.5 \text{ nsec}$
forward $(\cos \theta > 0.975)$	$0.75 \text{ GeV} \leq p_t < 8.0 \text{ GeV}$	$t < 2.0 \text{ nsec}$
	$0 \text{ GeV} \leq p_t < 0.75 \text{ GeV}$	$t < 1.0 \text{ nsec}$
Charged PFOs		
all	$0.75 \text{ GeV} \leq p_t < 4.0 \text{ GeV}$	$t < 3.0 \text{ nsec}$
	$0 \text{ GeV} \leq p_t < 0.75 \text{ GeV}$	$t < 1.5 \text{ nsec}$

- Track-only minimum p_t : 0.5 GeV
- Track-only maximum time at ECAL: 10 nsec